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FLYING QUALITIES OF SMALL GENERAL AVIATION AIRPLANES

Part 2. The Influence of Roll Control Sensitivity, Roll Damping, Dutch-roll Excitation, and Spiral Stability

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16. Abstract As the second phase of a study of flight characteristics criteria for small general aviation aircraft, experiments were conducted with a variable stability flying simulator to determine the influence of roll mode time constant, roll control sensitivity, and Dutch roll mode excitation due to lateral maneuvering in the landing approach; and spiral stability in IFR climb and cruise. The approach piloting task consisted of an ILS portion followed by a visual runway lineup maneuver requiring a 25° heading change. Conclusions are drawn with respect to optimum and minimum acceptable levels for roll mode time constant, roll control sensitivity and control power, and Dutch roll excitation parameters. The spiral tests indicate that although a moderate level of spiral stability aids heading tracking, the turbulence response of the airplane is likely to be excessive if this characteristic is obtained by aerodynamic means such as large dihedral. Where possible, the results are compared with requirements for piloted military airplanes.

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SYMBOLS AND NOTATION

I_x	moment of inertia about the roll axis (slug-ft^2)
I_y	moment of inertia about the pitch axis (slug-ft^2)
I_z	moment of inertia about the yaw axis (slug-ft^2)
I_{xz}	product of inertia (slug-ft^2)
IFR	instrument flight rules
ILS	instrument landing system
K_d/K_{ss}	Dutch-roll excitation parameter
L	rolling moment (ft-lb)
L_p	roll damping $\frac{1}{I_x}\frac{\partial L}{\partial p}$ (rad/sec^2 per rad/sec)
L_r	roll due to yaw rate $\frac{1}{I_x}\frac{\partial L}{\partial r}$ (rad/sec^2 per rad/sec)
L_β	dihedral effect $\frac{1}{I_x}\frac{\partial L}{\partial \beta}$ (rad/sec^2 per rad)
$L_{\delta a}$	aileron effectiveness $\frac{1}{I_x}\frac{\partial L}{\partial \delta_a}$ (rad/sec^2 per in)
L_φ	roll due to bank angle $\frac{1}{I_x}\frac{\partial L}{\partial \varphi}$ (rad/sec^2 per rad)
N	yawing moment (ft-lb)
N_p	yaw due to roll rate $\frac{1}{I_z}\frac{\partial N}{\partial p}$ (rad/sec^2 per rad/sec)
N_r	yaw damping $\frac{1}{I_z}\frac{\partial N}{\partial r}$ (rad/sec^2 per rad/sec)
N_β	directional stability $\frac{1}{I_z}\frac{\partial N}{\partial \beta}$ (rad/sec^2 per rad)

$N_{\delta a}$	aileron yaw $\frac{1}{I_z} \frac{\partial N}{\partial \delta a}$ (rad/ sec^2 per in)
$N_{\delta r}$	rudder effectiveness $\frac{1}{I_z} \frac{\partial N}{\partial \delta r}$ (rad/ sec^2 per in)
V	true airspeed (ft/ sec)
VFR	visual flight rules
j	$\sqrt{-1}$
p, $\dot{\varphi}$	roll rate (rad/ sec)
posc/ pav	measure of oscillatory component of roll rate and average roll rate (rudder pedals free)
p_{ss}	steady state roll rate (rad/ sec)
r, $\dot{\psi}$	yaw rate (rad/ sec)
rms	root-mean-square
s	Laplace transform operator $s = \sigma + j\omega$
β	sideslip angle (rad)
δ_a	aileron stick deflection (in)
δ_r	rudder pedal deflection (in)
ζ_d	Dutch-roll damping ratio
ζ_φ	damping ratio of numerator of $\frac{\varphi}{\delta a}$ transfer function
σ	real part of Laplace operator
σ_L	rms rolling moment disturbance per unit moment of inertia (I_x) due to gusts (rad/ sec^2)
σ_N	rms yawing moment disturbance per unit moment of inertia (I_z) due to gusts (rad/ sec^2)

τ_{rm}	roll mode time constant (sec)
τ_s	spiral mode time constant (sec)
φ	bank angle (rad or deg)
$\frac{\varphi}{\delta a}$	bank angle to control input transfer function

$$\frac{\varphi}{\delta a} = \frac{A_{\varphi_{\delta a}} (s^2 + 2\zeta_\varphi \omega_\varphi s + \omega_\varphi^2)}{(s + \frac{1}{\tau_s})(s + \frac{1}{\tau_{rm}})(s^2 + 2\zeta_d \omega_d s + \omega_d^2)}$$

$\lvert\frac{\varphi}{\beta}\rvert_d$	ratio of roll-to-sideslip at Dutch roll natural frequency
ψ_β	measure of lag between control input and sideslip response
ω	undamped natural frequency (rad/ sec)
ω_d	undamped natural Dutch-roll frequency (rad/ sec)
ω_φ	constant appearing in $\frac{\varphi}{\delta a}$ transfer function numerator (rad/ sec)
$(\zeta_d \omega_d)$	Dutch-roll real damping parameter (rad/ sec)

I. INTRODUCTION

In 1967 the FAA initiated a program to establish quantitative flying qualities criteria for small general aviation airplanes, sponsoring the Princeton variable stability Navion in a series of in-flight simulation experiments. The first phase, reported in Reference 1, explored the influence of large variations in dihedral effect, directional stability, and yaw damping.

This report presents the results of the second phase of the program wherein roll control sensitivity, roll damping, and Dutch roll mode excitation from aileron yaw and yaw due to roll rate were the primary variables. These were studied in the context of a simulated ILS approach in turbulent air ending in a runway lineup maneuver involving a 25° change in heading.

In addition a brief investigation of the effects of spiral mode stability and instability on the pilot's ability to perform IFR cruise and climb tasks was carried out. This was primarily in response to a request to provide information related to an FAA Advance Notice of Proposed Rule Making, Reference 2, which solicited comments concerning the need for natural or artificially augmented spiral stability for small airplanes. A recent investigation, Reference 3, had thoroughly covered the cruise aspect for airplanes in the small jet transport category, and additional data points for truly small airplanes were desired.

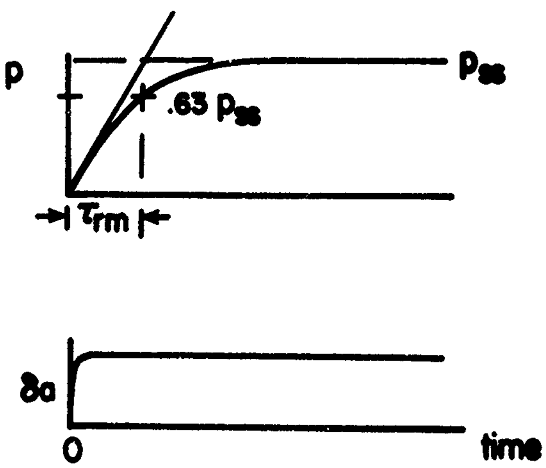
Background Discussion

Roll Mode Time Constant and Roll Control Sensitivity

Of the three modes of lateral-directional motion, the one which is most closely associated with intentional maneuvering is the so-called roll mode; the other modes, the spiral and the Dutch roll, involve motions which generally interfere with the pilot's desire to bank and unbank the airplane with some ease and precision.

If the airplane is rolled without yawing or sideslipping, the two "nuisance" modes will not appear, and the resulting roll rate may be described, for a step input, by the familiar first-order equation

$$p = \frac{L_{\delta a}}{L_p} (1 - e^{-t/\tau_{rm}}) \delta a = p_{ss} (1 - e^{-t/\tau_{rm}})$$



The defining factors of this response are a characteristic time, the roll mode time constant, τ_{rm}, and the initial roll acceleration. The first is a measure of the time which would be required to reach the steady-state roll rate if the roll acceleration continued at its initial value; it won't of course, because of the airplane's aerodynamic roll damping, L_p, so an alternate physical interpretation of this time constant is the time required for the roll rate to reach 63% $(1 - e^{-1})$ of its final value.

If τ_{rm} is short, then the roll control deflection commands roll rate - that is, a given deflection will produce, in a short time, a steady roll rate. Or, inversely, if a roll control deflection is removed, the airplane will quickly stop rolling. This leads to precise bank angle control, obviously a desirable situation.

Long roll mode time constants, on the other hand, cause the control to command roll acceleration - roll rate continues to build for a long time after the input, and the airplane is slow to stop rolling after it is removed. This situation is not conducive to precise control of bank angle.

It is easy to appreciate that the roll damping must have an intimate connection with this characteristic time, and in fact it is nearly equal to the inverse of the roll damping derivative, L_p, especially for short (less than .5 sec) time constants.

The initial acceleration, $\dot{p}$, is of course a function of how large the control input is, but also of the characteristic sensitivity, $L_{\delta a}$, the roll acceleration per unit control input. This quantity is a measure of control effectiveness and is determined by the type and size of control surface, flight condition, and the inertia characteristics of the machine. If the control input referred to above is measured at the cockpit controller, then $L_{\delta a}$ includes the effects of the gearing in the control system.

The role of these two parameters is well understood, and they have been the subject of extensive analysis and experimentation (References 4, 5, and 6 for example) but mainly for fighter and transport aircraft. Data have been lacking for the general class of small airplanes; the present work was undertaken to help fill that void.

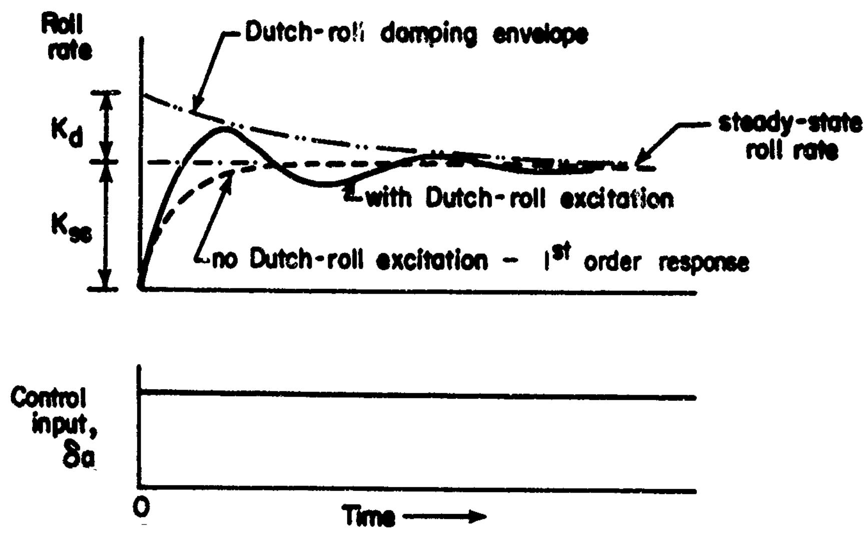
Dutch Roll Excitation from Aileron Yaw and Yaw Due to Roll Rate

The Dutch roll mode is not deliberately used by the pilot in the sense that he uses the roll mode for banking, but nonetheless it cannot be ignored because under some circumstances it can seriously interfere with precise control of the flight path.

In general, the Dutch roll will be excited whenever yawing or rolling moments or side forces are applied to the airplane. One source of such forces and moments is atmospheric turbulence and important aspects of that problem were explored in Reference 1. Other sources are control deflections and airplane motions themselves, however caused. Of these other sources, yaw due to aileron deflection, $N_{\delta a}$, and yaw due to roll rate, N_p, are the particular factors under investigation here.

Aileron yaw makes its effect felt at the instant of roll control deflection (assuming no appreciable aerodynamic lag, which is true for flap-type controls but not necessarily for spoilers), while N_p comes into play as soon as roll rate becomes significant. Yaw due to roll rate is almost always negative - right roll produces left yaw - and results from a forward inclination of the lift vector on the down-moving wing and vice versa. Aileron yaw can be either positive or negative depending upon the particular control configuration, and can be introduced artificially by interconnecting roll control and rudder surfaces.

The matter of interference with flight path control arises with respect to the response of the airplane to roll control inputs. Instead of being the nice approximate first order response sketched previously, the roll rate time history following a step input may contain an oscillatory component from the Dutch roll (the sketch presumes a neutral spiral mode):



Such oscillations obviously could interfere with precise roll control.

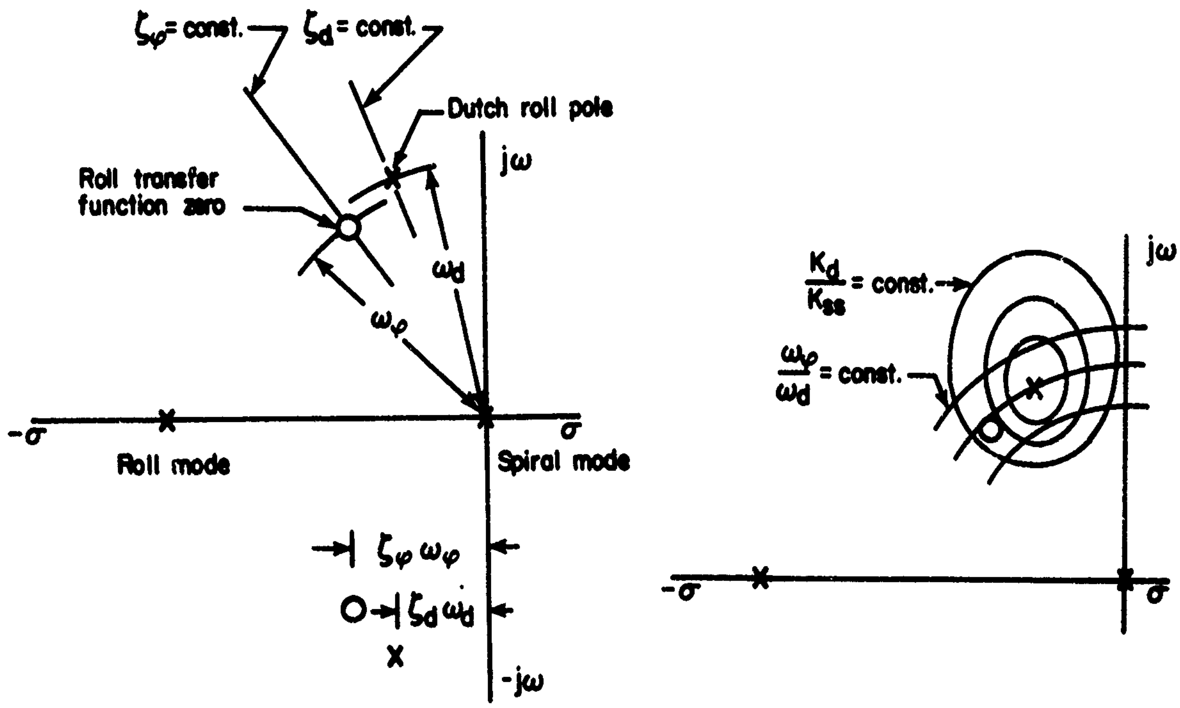
The matter has been extensively studied (References 6 and 7, for example) and several important parameters have been identified. The magnitude of the excitation is certainly important, and a convenient measure, at least from a research standpoint, is the ratio K_d/K_{ss}, which as seen from the sketch is the ratio between the roll rate due to the Dutch roll and the steady state roll rate at the instant of an abrupt step-like lateral control input, δa.

Another parameter is the ratio ω_φ/ω_d, an approximate literal expression for which is

$$\frac{\omega_\varphi}{\omega_d} \doteq \left(1 - \frac{N_{\delta a}}{L_{\delta a}} \frac{L_\beta}{N_\beta}\right)^{\frac{1}{2}}$$

Here ω_d is the true Dutch roll natural frequency and ω_φ is a constant appearing in the numerator of the transfer function of roll response to lateral control.* It is physically identifiable as the frequency of a special Dutch roll which would result if the wings could be held exactly level with the lateral control so that the oscillation would have only yawing and side-slipping motions.

This is most conveniently displayed by plotting the roots of the numerator ("zeros") and denominator ("poles") of this transfer function on the complex plane as shown in the sketch below:



Lines of constant $\omega_\varphi / \omega_d$ and the aforementioned K_d / K_{ss} may be displayed on this plot as indicated.

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$$\frac{\varphi}{\delta a} = \frac{A_{\varphi_{\delta a}} (s^2 + 2\zeta_\varphi \omega_\varphi s + \omega_\varphi^2)}{(s + \frac{1}{\tau_{sp}})(s + \frac{1}{\tau_{rm}})(s^2 + 2\zeta_d \omega_d s + \omega_d^2)}$$

It is known (see for example, Reference 4 or Reference 8) that the flying qualities problems associated with Dutch roll excitation are related in large part to the relative positions of the poles and zeros of the roll transfer function. This comes about because the separation is a function of the factors $N_{\delta a}$ and N_p: in general, positive increments of $N_{\delta a}$ move the zero upward with respect to the pole; positive increments of N_p move the zero to the right with respect to the pole.

The present investigation was designed to explore these Dutch roll excitation parameters in the context of small airplanes.

Spiral Mode

The spiral mode in light airplanes is often, perhaps even typically, unstable, but the divergence is slow enough that it goes unnoticed in situations where the pilot is actively controlling bank angle. However, the spiral has a history of association with accidents involving noninstrument-rated pilots in bad weather, and unusually quick divergence might add materially to the workload of the experienced instrument pilot, so the mode is not a trivial one.

The relationship between the characteristic time constant of the spiral mode, τ_{sp}, and the aerodynamic parameters of the airplane is indicated by the following approximate relationship (Reference 9):

$$\frac{1}{\tau_{sp}} \doteq \tau_{rm} \frac{g}{V} \left(\frac{L_\beta}{N_\beta} N_r - L_r\right)$$

The quantity in parentheses determines the stability of the motion, and indicates that large dihedral (L_β negative), and large yaw damping (N_r negative), favor spiral stability, while large directional stability (N_β positive) and roll due to yaw (L_r positive) favor instability. The roll damping is seen to have a direct bearing on the rate of convergence or divergence.

Although L_β, N_β, and N_r are more or less under the control of the designer, it is difficult to achieve a useful degree of spiral stability for all flight conditions; L_r is proportional to lift coefficient, and thus for low speed flight large geometrical dihedral and/ or low directional stability are required to keep $1/\tau_{sp}$ positive. This may lead to other piloting problems or to poor turbulence response at higher speeds (Reference 1).

An alternative to adjustment of aerodynamic stability derivatives to obtain spiral stability is available in the form of "wings-leveler" stability augmentation, which provides an artificial L_φ derivative. Such a system is examined in Reference 10.

II. EXPERIMENTAL PROCEDURE

The Variable Stability Navion. The variable stability airplane used in these experiments was derived from a North American Navion airframe and is pictured in its current (1969) configuration in Figure II-1. Significant changes from earlier configurations described in References 1, 4, and 11, include angle of attack and sideslip vanes relocated on spanwise extending booms, and replacement of electro-mechanical rudder and elevator servos with high performance hydraulic units.

Figure II-2 shows the cockpit interior with the stick controller installed, and Figure II-3 with the wheel controller. The stick was used in the Dutch roll excitation and roll mode experiments, and the wheel in the roll mode tests and in the spiral investigation. The evaluation pilot is seated on the right, and his controls provide only electrical inputs to the control system servos. Fixed feel is provided by springs; force gradients and control travel are given in Table 1 below:

TABLE 1

CHARACTERISTICS OF EVALUATION PILOT'S CONTROLS

Controller	Travel	Gradient
Stick Lateral	±3 in	4 lb/in
Stick Longitudinal	±5 in	4 lb/in
Wheel	$\pm 90^{\circ}$	.19 lb/deg (2.2 lb/in at grip)
Rudder Pedals	±5 in	25 lb/in

Breakout forces and hysteresis are negligible. The safety pilot's left seat controls are the standard Navion mechanical system.

FIGURE II-1 VARIABLE STABILITY NAVION FLYING SIMULATOR
(1969 CONFIGURATION)

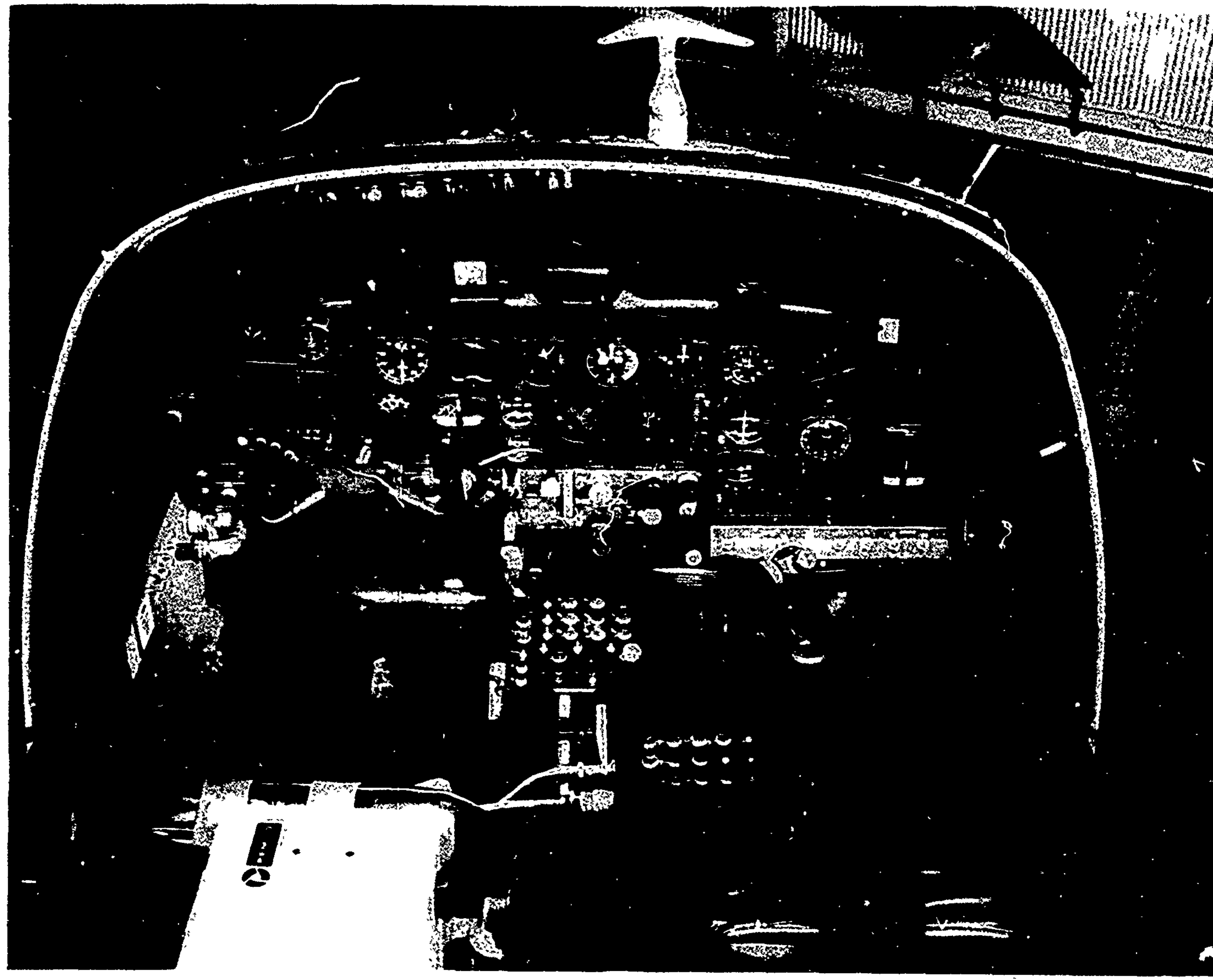

FIGURE II-2 COCKPIT LAYOUT – STICK CONTROLLER

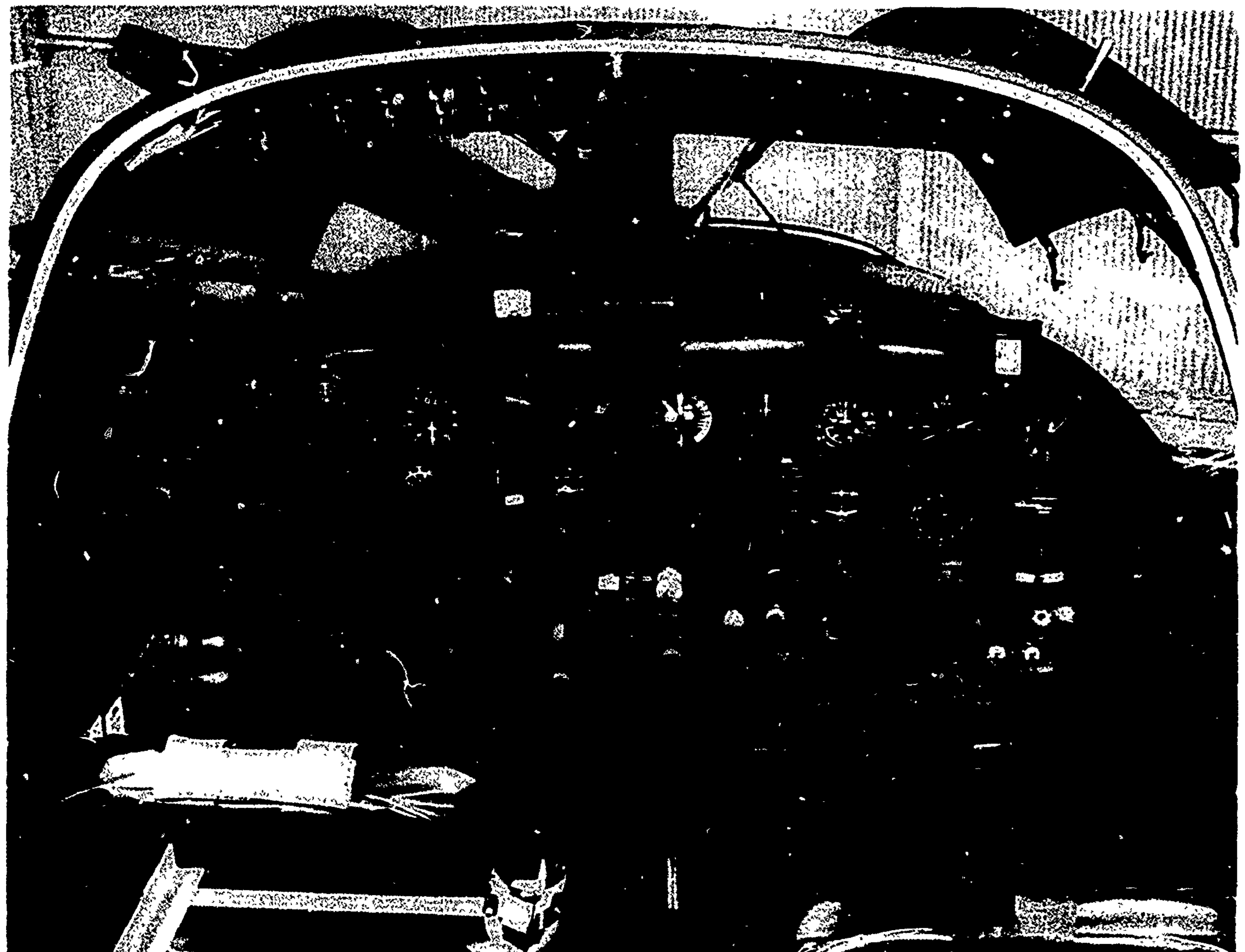

FIGURE II-3 COCKPIT LAYOUT - WHEEL CONTROLLER

The overhead panel and between-seats console contain the controls for changing stability derivatives and turbulence parameters. As used in these experiments, the stability and damping of the roll, pitch, yaw and heave motions, and the sensitivity of roll, pitch, and yaw controls could be varied. The analog matching procedure described in Reference 4 was used to achieve a close correspondence between the Navion's response and an analog computer simulation of the test configuration.

Turbulence Simulation. The disturbances produced by a turbulent atmosphere with rms linear velocity components of about 5 ft/sec were simulated. Traversing this field of turbulence at 105 knots produced equivalent rms sideslip (β) of about 1.6 degrees. According to Reference 8 (Section 3.7.3, Figure 2) the probability of equaling or exceeding this rms gust velocity once turbulence is encountered is about 10%.

The actual turbulence simulation was achieved by introducing signals representing vertical gusts, side gusts, and spanwise gradient of vertical gusts to the control surface servos as shown in Figure II-4. The signals themselves began as Gaussian white noise which was prefiltered with 40 db/decade attenuation below .05 cps and 20 db/decade above 4 cps (longitudinal channel) and above 2 cps (lateral channels). The low pass filtering reduced high frequency servo excitation, while the high pass filtering was introduced to exclude the possibility of servo-saturation and to eliminate a steady sideslipping condition associated with a steady lateral gust which occurs when the side forces due to gusts are not simulated.

The three uncorrelated noise signals are then passed through the filter circuitry shown in Figure II-5. Spectral shaping is carried out by varying the filter break frequencies and by adjusting the gains to match the amplitudes associated with particular rms gust velocities. The asymptotes of the simulated spectra are shown in Figure II-6. First-order Padé transport lag approximations account for the finite separation of vertical

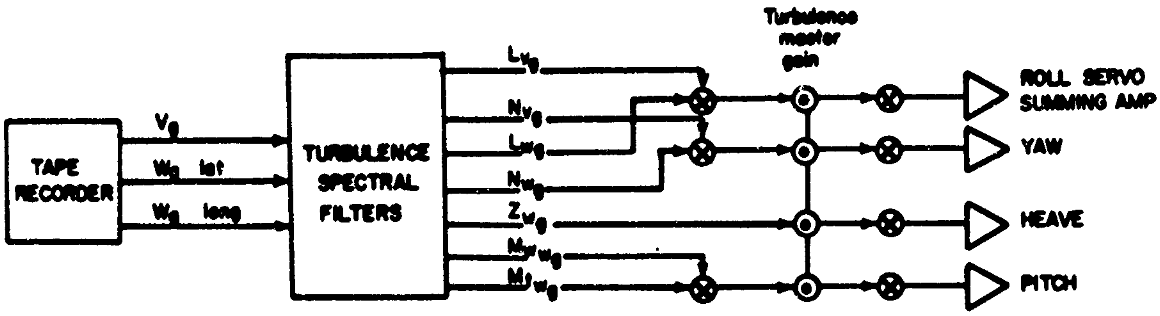

FIGURE II-4 TURBULENCE SIMULATION SYSTEM

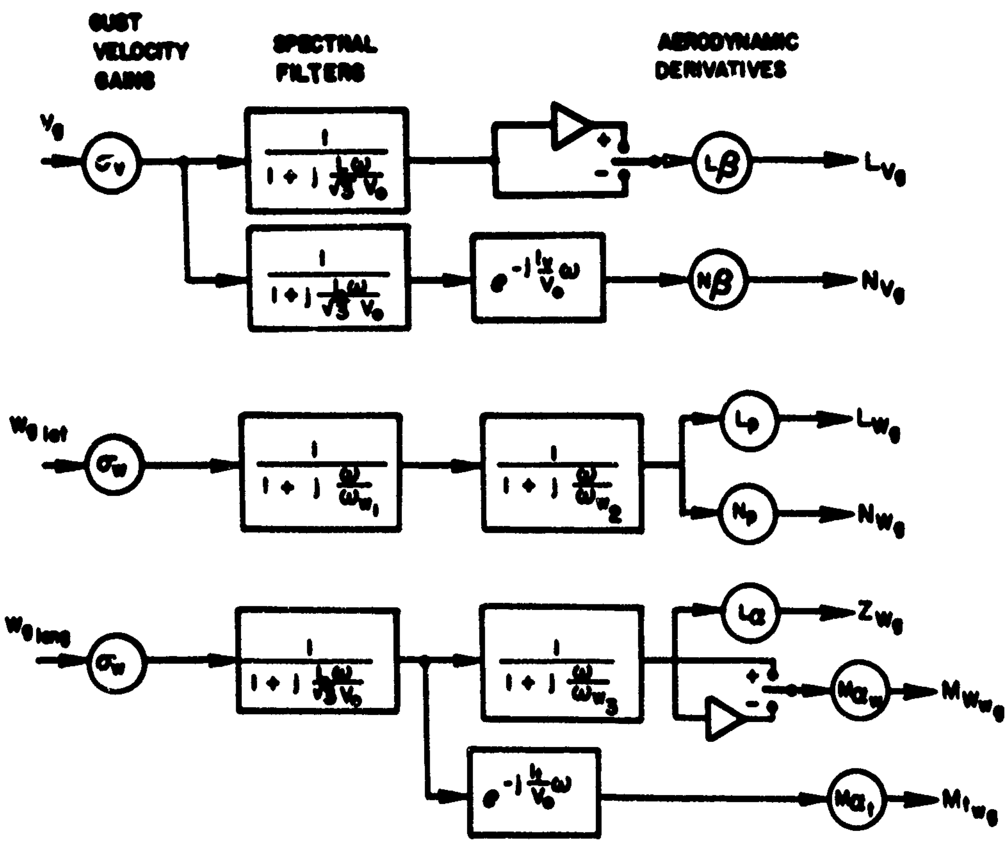

FIGURE II-5 TURBULENCE SPECTRUM FILTER SYSTEM

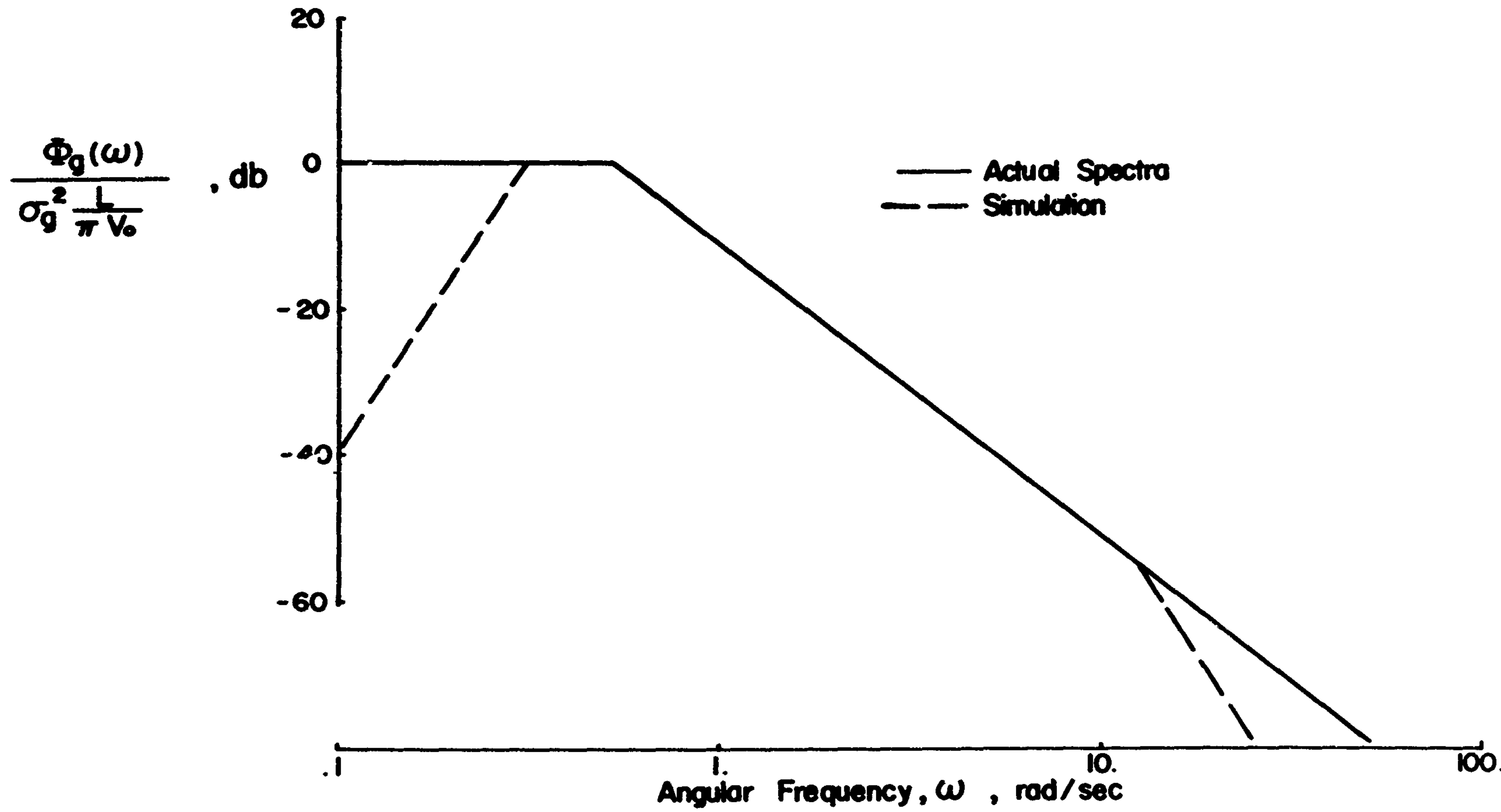

FIGURE II- 6 ASYMPTOTES OF ACTUAL AND SIMULATED TURBULENCE SPECTRA and horizontal tail from the wing. The resulting signals are further scaled to match the aerodynamic stability derivatives being simulated.

Configurations

Roll Mode Time Constant and Roll Control Sensitivity Experiments

Four values of roll mode time constant were tested: τ_{rm} = 0.1, 0.25, 0.50, and 1.0 seconds. The other airplane dynamic characteristics were held constant at the following levels:

$$\omega_d = 2.3 \text{ rad/sec}$$

$$\zeta_d = 0.10$$

$$L_\beta = -16 \text{ rad/sec}^2\text{/rad}$$

$$1/\tau_{sp} \doteq 0$$

$$N_{\delta a} = 0$$

The specific stability derivative values used are listed in Table 3, and analog computer responses to step aileron inputs are shown in the Appendix.

Experiments were run with both stick and wheel cockpit controllers. The range of $L_{\delta a}$ tested was from $L_{\delta as}$ = 0.7 to 7 rad/sec^2/in for the stick and $L_{\delta aw}$ = 1.5 to 15 rad/sec^2/rad. Maximum control deflection was ±3 inches for the stick and ±90° for the wheel; force gradients were fixed at 4 lb/in for the stick and 2.4 lb/in for the wheel. The force versus deflection characteristics were linear, with no perceptible breakout or hysteresis.

Dutch Roll Excitation Experiment

The position of the roll-to-aileron transfer function zero with respect to the pole was varied mainly by adjusting the derivatives $N_{\delta a}$ and N_p although small changes in other stability derivatives then had to be made in order to keep the Dutch roll characteristics constant. Derivative and parameter values are given in Table 4, using the following designator system:

Example: H 96 14

Dutch roll frequency $\frac{\omega_\varphi}{\omega_d} \times 100$ $\zeta_\varphi \times 100$

H for ω_d = 2.3 rad/sec

L for ω_d = 1.3 rad/sec

Pole-zero relationships with overlays indicating K_d/K_{ss} values are shown graphically in Section IV, Results and Discussion.

Two levels of Dutch roll frequency, ω_d = 1.3 and 2.3 rad/sec, were tested. Constant values were picked for other parameters:

Dihedral effect	L_β = -16 rad/sec^2/rad
Dutch roll damping	ζ_d = 0.10
Roll damping	τ_{rm} = .25 sec
Spiral stability	$1/\tau_s \doteq 0$ 1/sec
Roll sensitivity	$L_{\delta as} \doteq 2$ rad/sec^2/in

The experiments used only the stick controller. The evaluation pilot was allowed to optimize the rudder sensitivity starting from a nominal value of $N_{\delta rp}$ = -.3 rad/sec^2/in.

Analog computer responses to step aileron inputs are shown in the Appendix.

Spiral Mode Experiments

Two levels of spiral stability were tested, a stable case with time to half amplitude of 7.7 sec and an unstable case with time to double amplitude of 8.7 seconds. These were obtained on the variable stability airplane by adjusting the level of dihedral (L_β = -24 rad/sec^2/rad for the stable machine and L_β = 0 for the other) and the level of the roll due to yaw rate derivative (L_r = 1.0 rad/sec^2/rad/sec for the stable case, L_r = 2.0 for the unstable one).

Other airplane characteristics were held fixed at favorable levels:

Roll damping	$\tau_{rm} = .25$ sec
Dutch roll frequency	1.8 rad/sec
Dutch roll damping	$\zeta_d = 0.1$
Wheel sensitivity	7 rad/sec^2/rad
Aileron yaw	$N_{\delta aw} = 0$

Piloting Task - Roll Mode, Roll Control Sensitivity, and Dutch Roll Excitation Experiments

The flight phase selected for the experiments was the landing approach shown in Figure II-7, specifically, a simulated ILS approach to 200 feet, continued visually down to a 20 foot wave-off altitude. This final maneuver required a nominal change in heading of 25°.

Flight procedure called for setting up the configuration on the downwind leg of the approach, engaging the variable stability system, and giving control to the evaluation pilot who wore an instrument hood. A minute or so of "feeling out" the configuration was allowed, followed by a 135° left turn to intercept the localizer. The localizer was usually intercepted at a point which allowed a minute or so of level flight tracking before intercepting the glide slope. Just prior to glide slope intercept, about 3-1/2 miles from the threshhold, the artificial turbulence would be turned on, signalling the beginning of the actual evaluation. Localizer and glide slope tracking continued down to 200 ft above the surface, at which point the hood would be removed and the visual offset maneuver completed. The safety pilot would take control of the airplane for the go-around.

During the turn to downwind and climb back to altitude the evaluation pilot would transmit his comments and ratings which were recorded on the ground.

The ILS signals were provided by an ADCOLE microwave unit, on loan from FAA NAFEC. Standard cross-pointer cockpit instrumentation

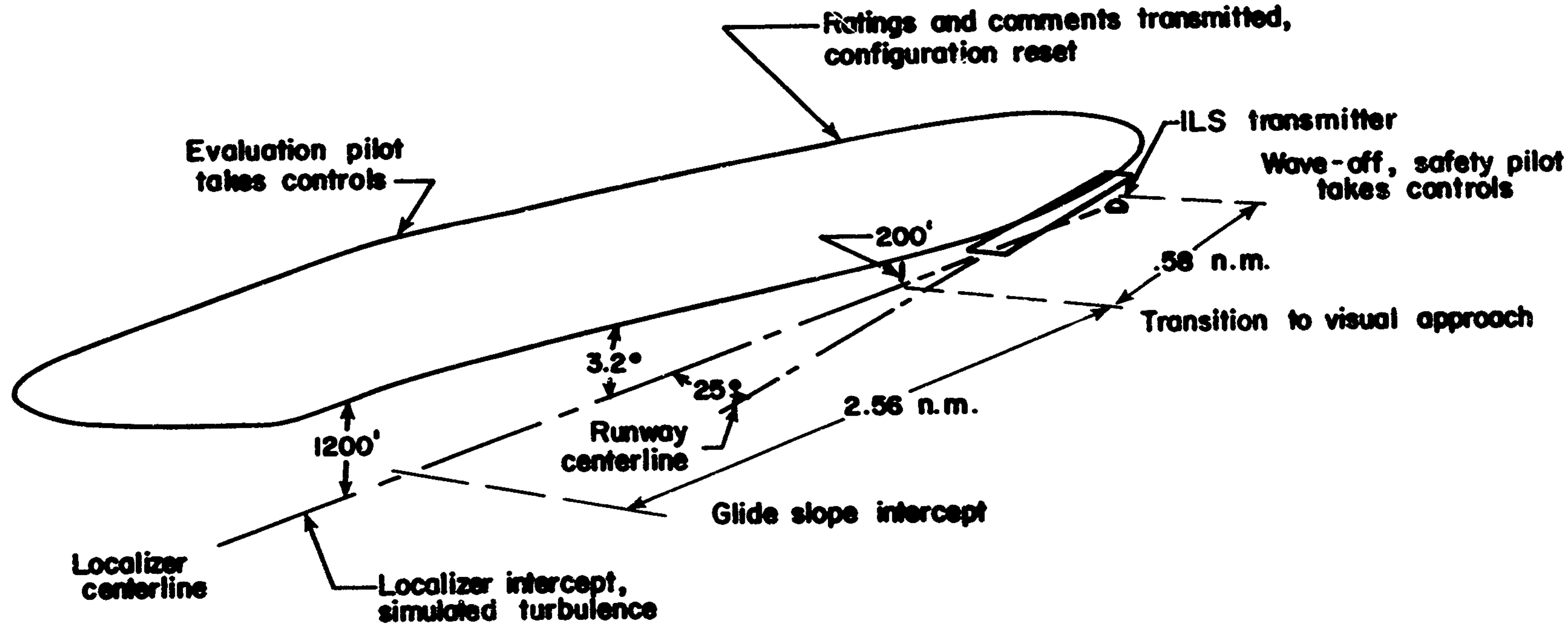

FIGURE II-7 DIAGRAM OF SIMULATED APPROACH was used (the upper indicator in Figure II-2). Glide slope angle was set at 3.2°, a value dictated by terrain avoidance requirements.

It should be noted that this task differed in several respects from that used in the previous phase of the program (Reference 1); that work made use of a standard ILS system (Trenton, N.J.) with 3.0° glide slope. This was significant in that the localizer was intercepted at about 5 miles and the glide slope at 4.5 miles and 2000', thus affording slightly longer evaluation time. No visual turning maneuver at the end of the approach was possible.

Piloting Task - Spiral Stability Tests

For the spiral stability tests the airplane was turned over to the evaluation pilot in an initially trimmed condition, either in level flight for the cruise test, or climbing at maximum continuous power for the climb experiment. An airspeed of 105 kt was used in both cases; this was neither normal cruise nor normal climb speed, but rather a convenient value for which many configuration parameters were already known.

The task involved flying heading vectors, intercepting and tracking VOR radials, copying and reading back simulated clearances, looking up radio frequencies, and exploring the general handling of the airplane on instruments. The climb test included frequent new altitude assignments, which added power changes and attendant need for retrimming the airplane to the overall workload.

Although the airplane has 3-axis trim, the pilot was not allowed to alter the roll trim from the setting which gave initial equilibrium in deference to the fact that most small airplanes do not have that feature. Adjustment of rudder trim was allowed.

About 45 minutes was spent evaluating each configuration in each of the two flight conditions. A small amount of "feeling out" in smooth air was allowed, but in general the tests were flown with simulated turbulence appropriate to the stability derivatives.

Data Collection

Pilot ratings. The primary data consisted of pilot ratings and commentary. Evaluation pilots were asked to use the so-called Cooper-Harper scale of Reference 12, reproduced here as Figure II-8.

Commentary to supplement the ratings was requested, and was tape recorded after each run. Normally ratings and comments would be obtained after each approach, but requests for additional runs before rating a configuration would be honored. The commentary was transcribed for use in analysis of the rating data, and although too voluminous for inclusion in the report, paraphrased and, in some cases, directly quoted comments are used in the discussion of results.

Other data. Measurements of airplane motions, pilot activity, and task performance were relayed to the ground via a telemetry link and recorded on magnetic tape. The first category included yaw rate, roll rate, and airspeed; the second, stick (or wheel) and rudder pedal motions; localizer and glide slope deviation were measures of task performance.

Many of these parameters were replayed onto a strip chart recorder and examined for correlation with ratings and commentary. Some of this material appears in the discussion of the results. Manual numerical analysis of zero crossings and slope reversals was carried out in some cases. Digital processing to obtain extensive statistical information is available but was not used for this particular report.

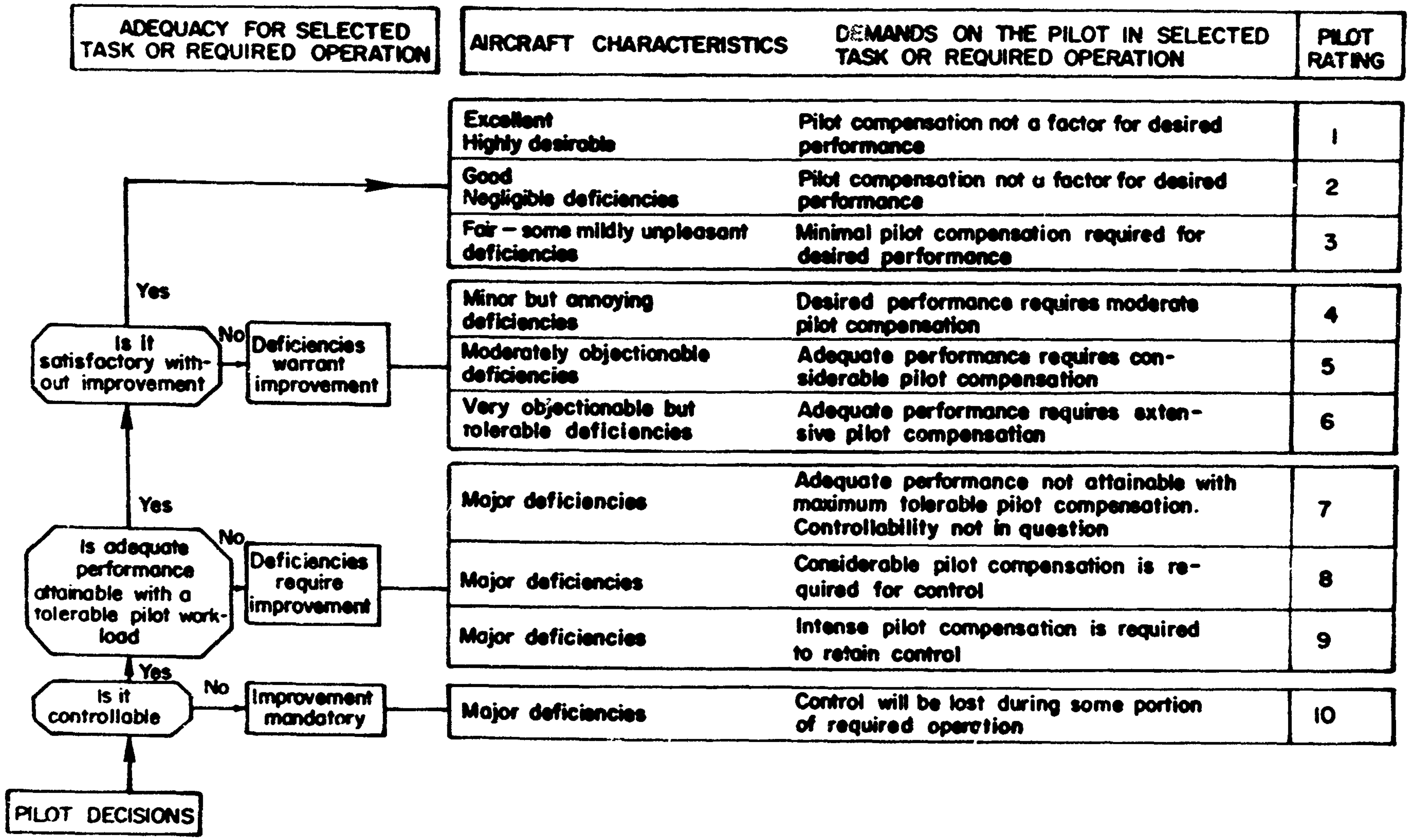

FIGURE II-8 HANDLING QUALITIES RATING SCALE

III. RESULTS AND DISCUSSION - ROLL MODE TIME CONSTANT AND ROLL CONTROL SENSITIVITY

The pilot rating results of the roll mode time constant - roll control sensitivity experiments are shown in Figures III-1a through III-1d for the center stick controller and Figure III-2 for the wheel controller. It should be explained that the stick was installed for most of the approaches of this phase, with comparatively little data being gathered with the wheel. This was not out of preference for the stick control; and in fact, it was appreciated that most general aviation airplanes use the wheel-type control. However, it was anticipated that the general trends of the results would be independent of the type of controller, and once these were established using one form, confirmation and numerical values for the other type could be established with relatively few runs. This proved to be the case. In addition, the center-stick data could be compared directly with the work of Reference 4 which dealt with visual approaches.

Effects of Roll Control Sensitivity with $\tau_{rm} = .25$ sec.

For each roll mode time constant there is seen to be a "best" level of roll sensitivity, $L_{\delta as}$ or $L_{\delta aw}$, though in general this optimum is not sharply defined. An examination of the specific effects of changing $L_{\delta a}$ while holding the roll damping fixed at a "good" level - $\tau_{rm} = .25$ sec - provides some insight into the reasons for this.

High Roll Control Sensitivity. As seen in Figures III-1 or III-2 for $\tau_{rm} = .25$ sec, increasing $L_{\delta as}$ from 3.5 to 7 rad/ sec^2/ in, or $L_{\delta aw}$ from 7.5 to 15 rad/ sec^2 / rad resulted in a one unit degradation in rating. Here the lower sensitivity elicited the comment, ".... a nice airplane...... Dynamics were nice, control sensitivities were nice. Just a little bit too much turbulence....to give it a 2.5...." The higher sensitivity, which for the wheel case was about twice that of the basic airplane - full aileron fcr

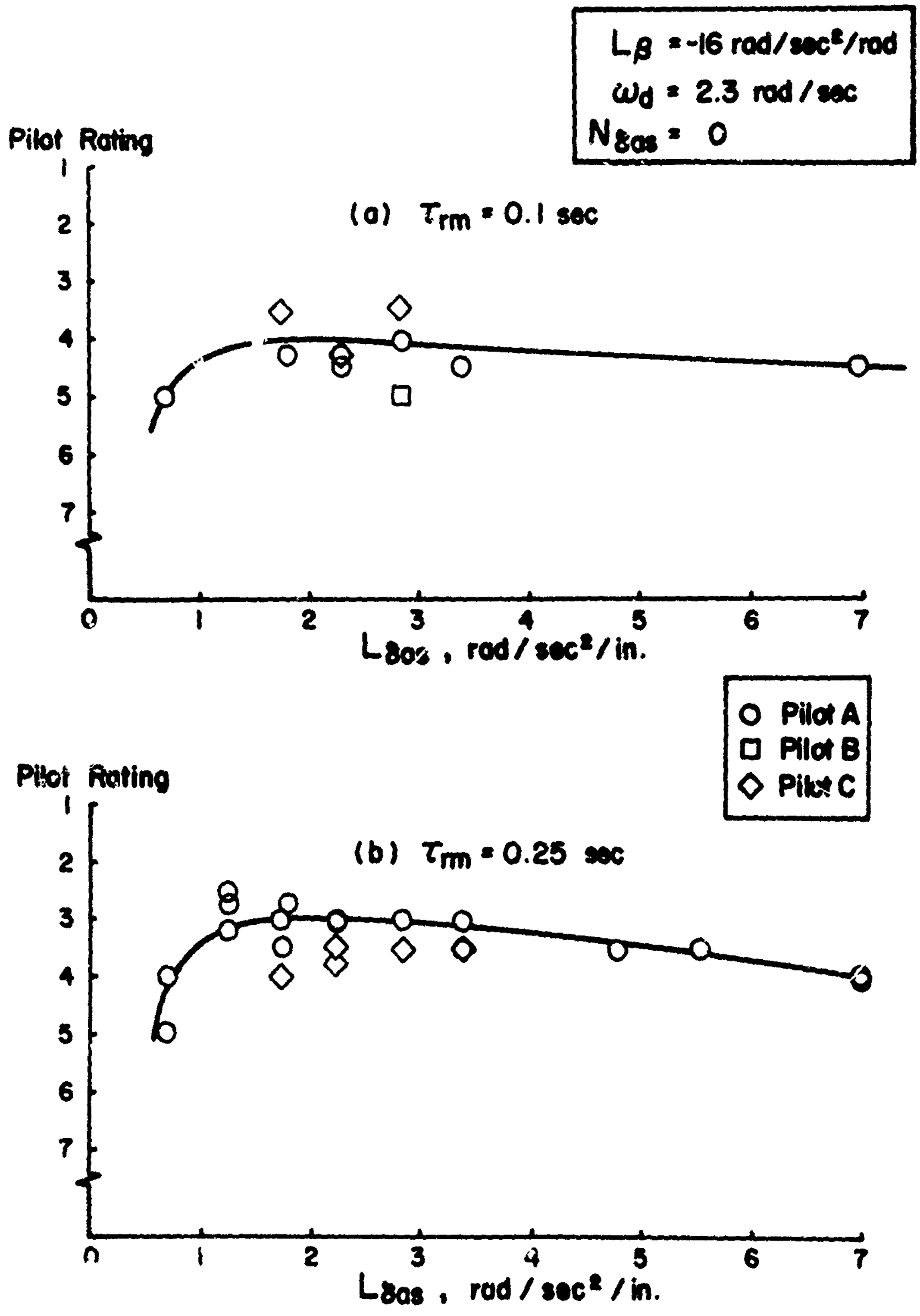

FIGURE III-1 PILOT RATING AS A FUNCTION OF ROLL SENSITIVITY, $L_{\delta as}$. STICK CONTROL.

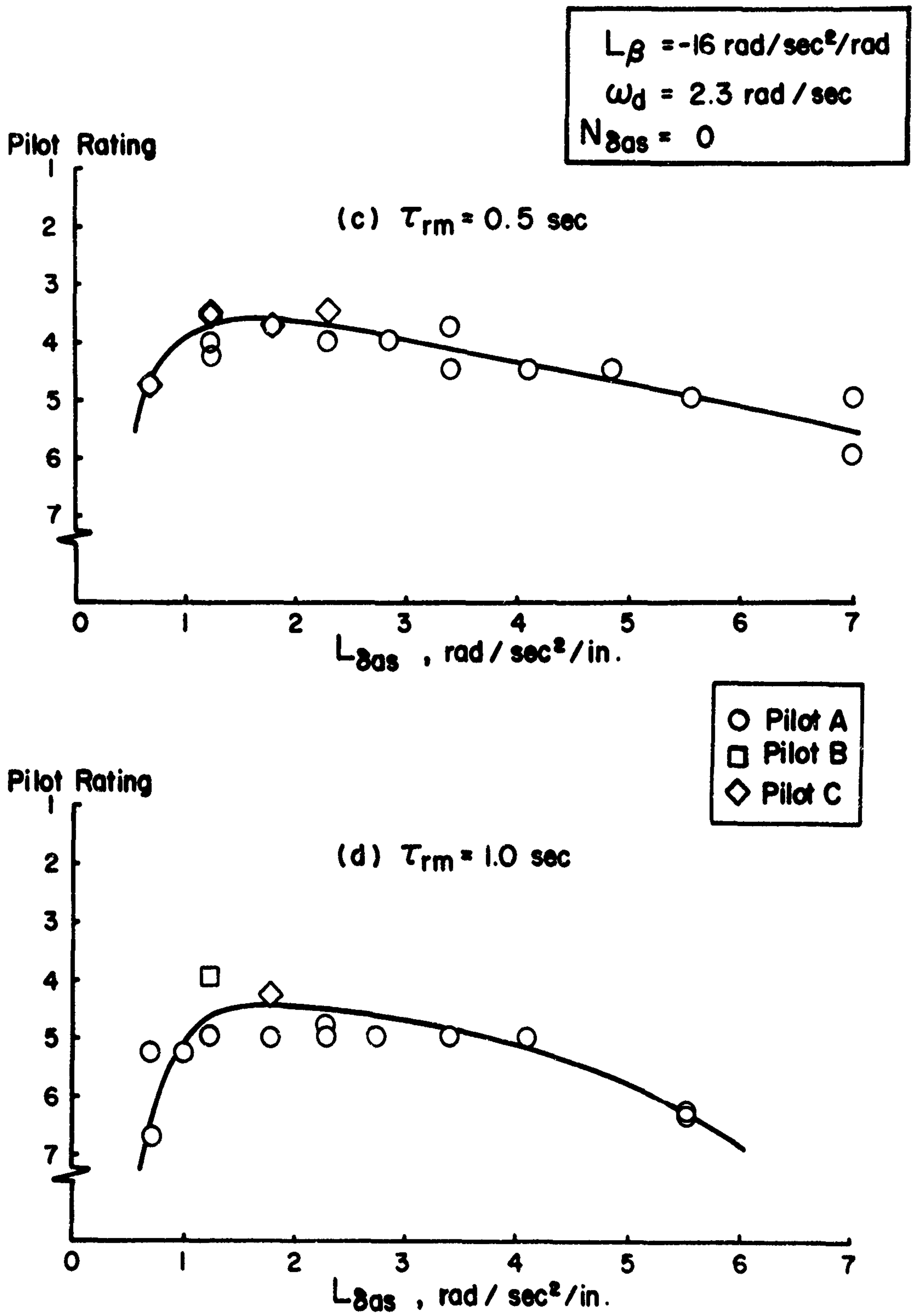

FIGURE III-1 Concluded

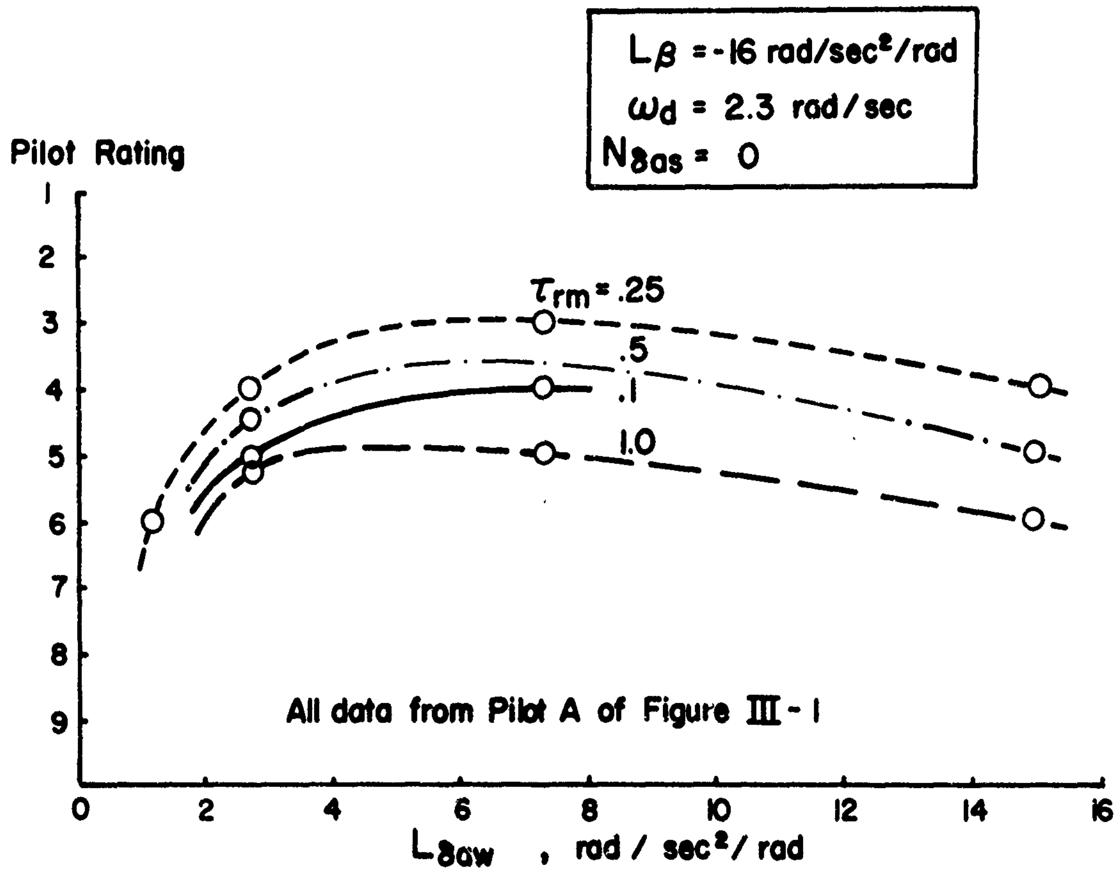

FIGURE III - 2 PILOT RATING AS A FUNCTION OF ROLL SENSITIVITY, $L_{\delta aw}$. WHEEL CONTROL.

45° of wheel throw instead of 90° - resulted in the comment, "It's a nice airplane as far as I could tell in dynamics. Just a very high [wheel] gain." The pilot commented further that he had to (and could) compensate by lowering his own gain, and he rated it a 4. His comments for the stick controller were similar.

Thirty-second portions of this pilot's runs with τ_{rm} = .25 sec and $L_{\delta aw}$ = 7.5 and 15 rad/ sec^2 / rad, shown as Figure III-3, do show generally smaller magnitude wheel motions for the higher sensitivity case. Inspection of ninety seconds of the mid-portion of each approach indicates that the overall activity of the pilot-airplane combination becomes slightly higher when $L_{\delta a}$ is increased as indicated in Table 2 below:

TABLE 2

MEASURES OF ACTIVITY DURING 90 SECONDS OF APPROACH, τ_{rm} = .25 sec, $L_{\delta aw}$ = 7.5 and 15.0 rad/ sec^2 /rad

Measure	$L_{\delta aw}$, rad/ sec^2 / rad 7.5	15.0
Roll rate zero crossings	103	121
Wheel deflection zero crossings	80	103
Roll rate trace slope reversals	156	169
Wheel deflection slope reversals	117	134

However, the pilot is evidently not having problems of overcontrolling or inducing large unwanted motions. At least for the .25 sec roll mode time constant case, $L_{\delta aw}$ = 15 (or $L_{\delta as}$ = 7) should be considered higher than desirable but not excessive.

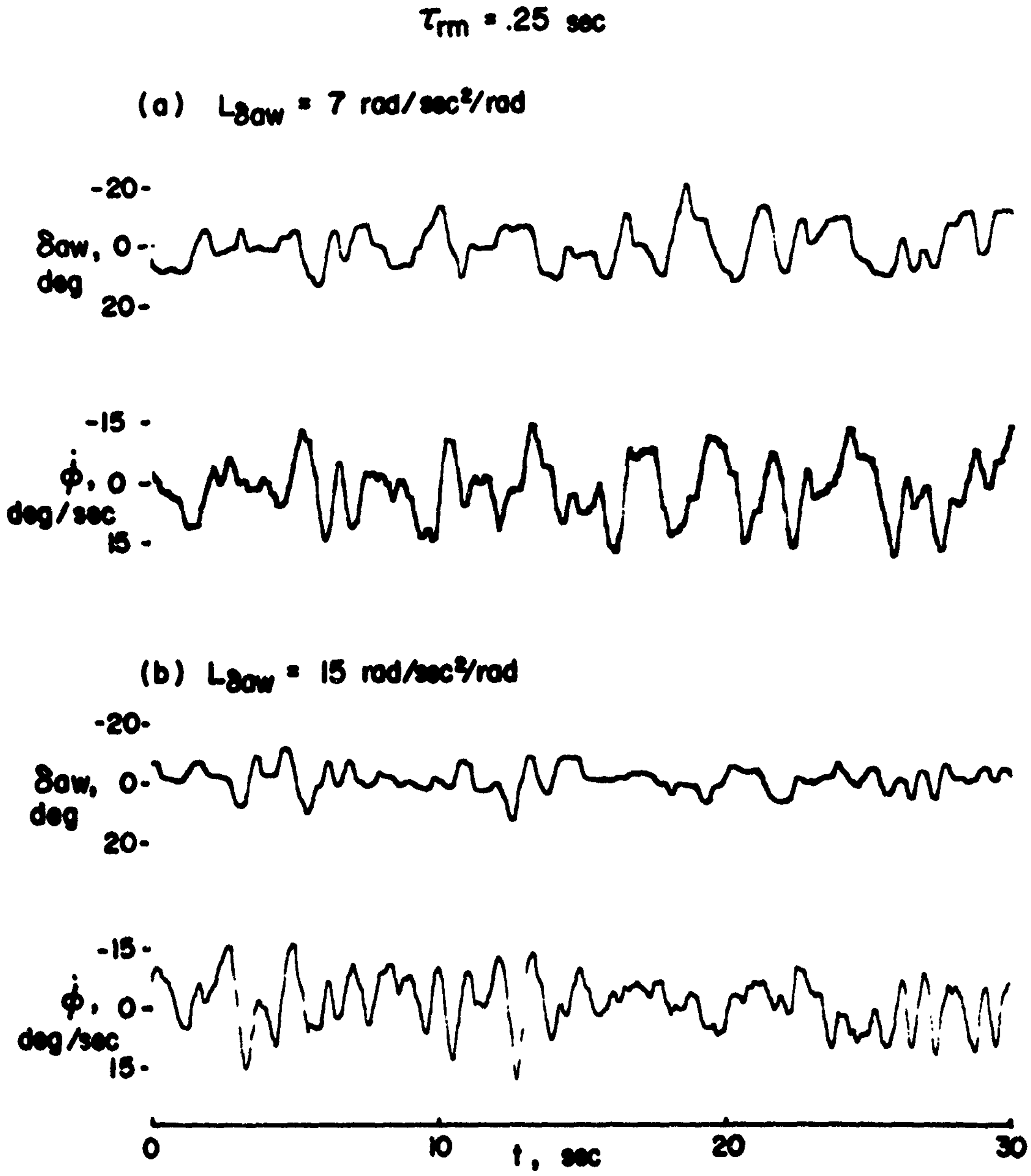

FIGURE III-3 EFFECTS OF HIGH ROLL CONTROL SENSITIVITY, τ_{rm}=.25 SEC WHEEL CONTROL, δaw AND $\dot{\phi}$ VS TIME

Also pertinent to this discussion of the results from the standpoint of high sensitivity, is the fact that the ILS task itself apparently tended to suppress some of the effects of higher-than-optimum $L_{\delta a}$. That is, although the presence of sensitive roll control might be noted during the "feel-out" portion of the run before intercepting the localizer, once the pilot became established on the beam his rolling maneuvers were generally small, involving intentional small amplitude banking to effect heading changes and recovery from gust upsets. Also, being under the hood made him less able to perceive small airplane motions, since his scan had to include several instruments in addition to the attitude indicator. Often a judgment of excessive sensitivity would be based upon the visual line-up portion of the approach, a phase of the task which involved larger-scale maneuvering (20°-30° bank, then unbank) than the instrument portion.

Low Roll Control Sensitivity. The data presented in Figures III-1 and III-2 indicate that although the region of best sensitivity is not sharply defined, for values of $L_{\delta as}$ less than about 1.5 rad/sec^2/in (or $L_{\delta aw}$ less than 3.0 rad/sec^2/rad) a marked degradation of flying qualities is to be expected.

For τ_{rm} = .25, the problem is described as one of having to move the wheel too far to get the desired roll performance. The larger wheel motions are evident in the time histories of Figures III-4a and b which compare approaches with $L_{\delta aw}$ = 7 (rated 3.0) and $L_{\delta aw}$ = 3 (rated 4-4.5). The roll sensitivity for the former is described as "....nice....not too much but not too little," while the latter elicits ".... [there] just wasn't enough control power, I had to work rather hard. Too much travel required on the wheel... not really considerable compensation, just quite annoying."

Cutting $L_{\delta aw}$ by a factor of two again, down to 1.5, causes a striking degradation to a rating of 6. The commentary cited low sensitivity, difficulty in recovering from turbulence upsets, and not enough controllability in the visual lineup maneuver. A typical flight record (a portion is shown in Figure III-4c) confirms the use of wheel deflections greater than $\pm 50^\circ$ on

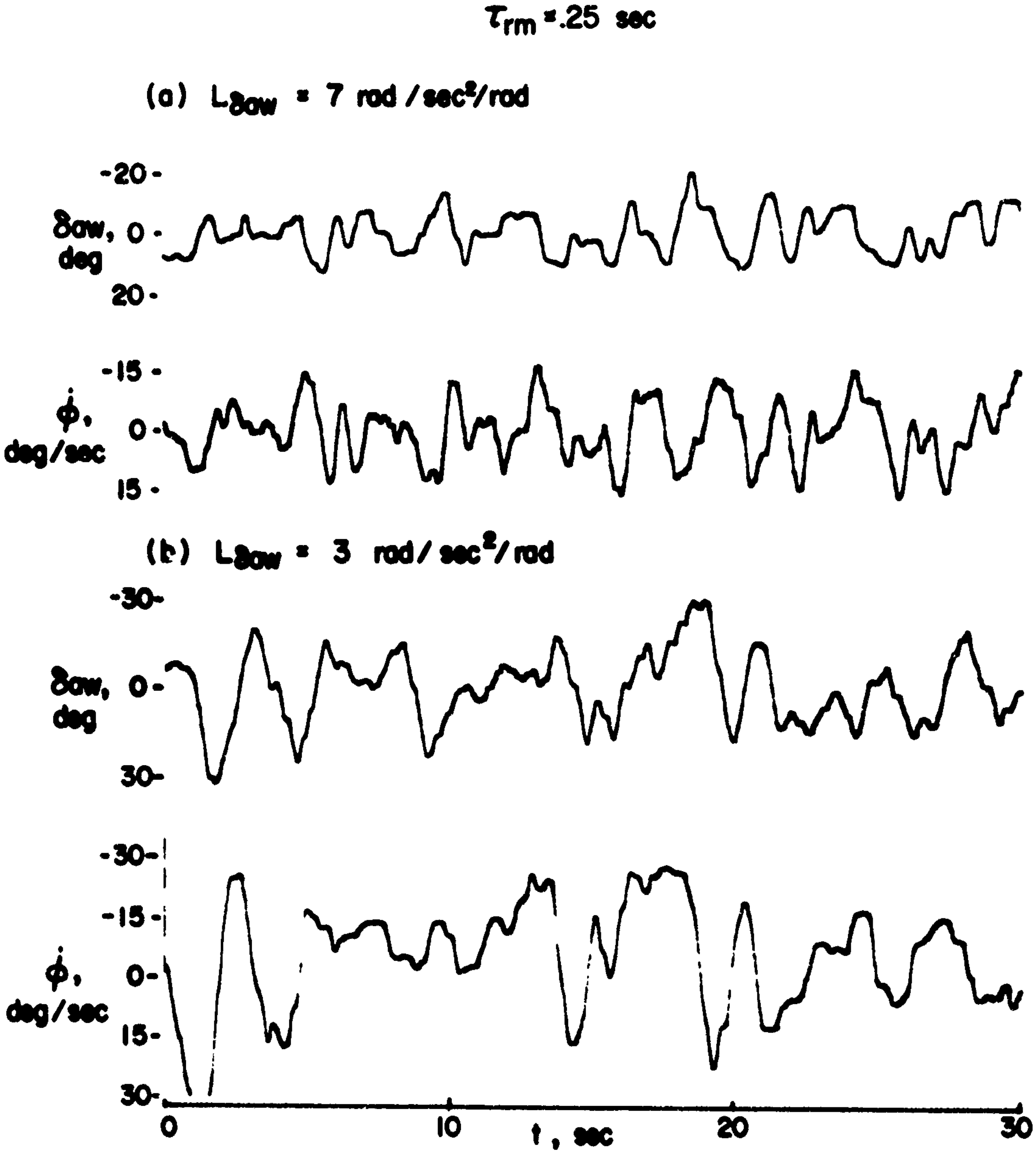

FIGURE III-4 EFFECTS OF LOW ROLL CONTROL SENSITIVITY, τ_{rm} = .25 SEC WHEEL CONTROL, δaw AND $\dot{\phi}$ VS TIME

τ_{rm}=.25 sec

(c) $L_{\delta aw}$ = 1.5 rad/sec²/rad

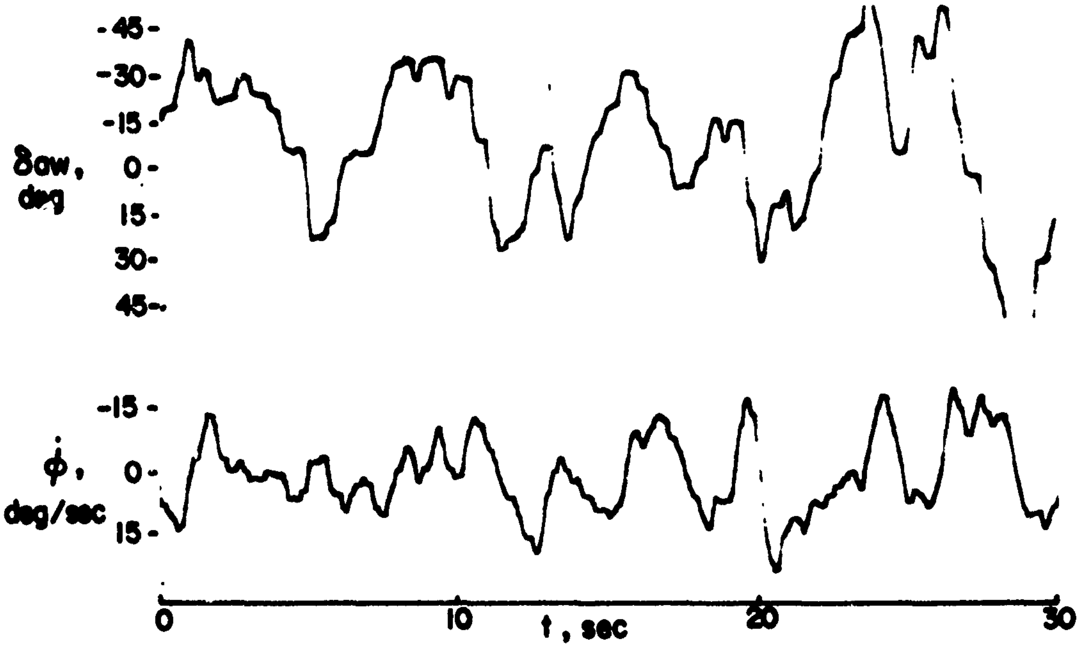

FIGURE III-4 Concluded

occasion, although this is not really close to the ±90° stops. The full throw was almost never used, perhaps because of the physiological difficulties of one-handed operation. There is an indication here that while wheel motions of ±10° (±.9 inches at the rim of the wheel, ± 2 lb of force) are acceptable, ±20° is becoming objectionable.

For the center-stick controller the lower limit for adequate sensitivity appears to be about $L_{\delta as} = 1.25$ rad/sec^2/in - that is, for each τ_{rm} the ratings drop sharply for smaller $L_{\delta as}$ settings (Figures III-1a through d). The $\tau_{rm} = 0.25$ sec, $L_{\delta as} = 0.7$ airplane, for example, drew the comment that the dynamics were reasonable but the low sensitivity led to an objectionably high physical workload. This is borne out by the time history of that approach, a portion of which is shown as Figure III-5a. For comparison a run with "good" sensitivity, $L_{\delta as} = 1.8$, is also shown as Figure III-5b.

Effects of Roll Damping with $L_{\delta a}$ Optimum

The results shown in Figures III-1 and III-2 confirm that the level of flying qualities depends upon the amount of roll damping present; this variation will now be examined for configurations which have optimum control sensitivity.

For either stick or wheel controller, $\tau_{rm} = .25$ sec was judged to be best - a comfortable configuration with which good bank angle control could easily be achieved. The commentary indicated that the only downgrading factor was the level of turbulence upsets.

Increasing τ_{rm} to 0.5 sec, still with optimum control sensitivity, results in a degradation of about one rating unit. This level of damping is characterized as "low," and the airplane seems "loose" in roll. The pilot is confronted with a more difficult problem in the roll axis than with τ_{rm} = .25 sec - the rolling motions associated with the Dutch roll are now larger* due to the lower roll damping. Whereas for higher levels of roll damping

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*$|\varphi/\beta|_d = 1.7$ for $\tau_{rm} = .25$, and $= 3.45$ for $\tau_{rm} = .50$

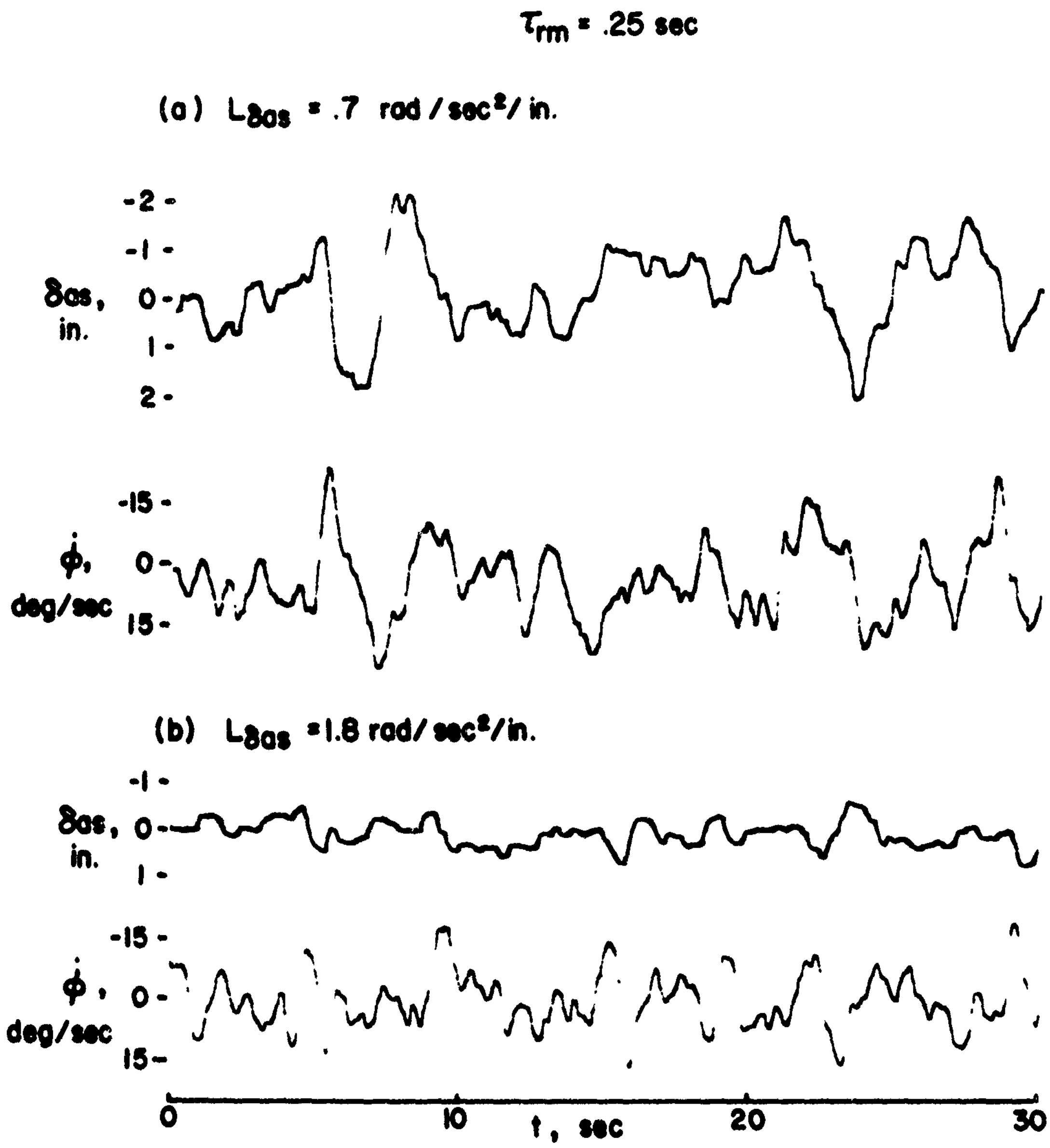


FIGURE III-5 EFFECTS OF LOW CONTROL SENSITIVITY, τ_{rm}=.25 SEC STICK CONTROL, δas AND $\dot{\phi}$ VS TIME the rolling motions associated with the Dutch roll are relatively innocuous, and pose no particular piloting problem, the excursions that accompany the lower damping are large enough to deserve comment to the effect that the workload involved in controlling this "wing waving" is markedly greater. There is a tendency to overshoot a desired bank angle because the airplane does not stop rolling immediately so that in the process of correcting an upset the airplane usually will roll too far, and several control movements are required to reach the desired equilibrium position.

Increasing the roll mode time constant even more, to 1.0 sec, makes the roll problem still more difficult. With near-optimum $L_{\delta as}$, a pilot commented on the difficulty of roll control in turbulence and the high level of stick activity. As may be noted from Figure III-1d, this configuration is rated nearly two units worse than the quarter-second time constant airplane in the "good" control sensitivity region.

Going back now to the case of highest roll damping, $\tau_{rm} = 0.1$ sec, we see about a one unit degradation compared to the .25 second airplane. Unlike the lower damping cases, however, the problem here is not with airframe dynamics, but rather with turbulence excitation in roll associated with large L_p. This was an annoying factor, with the pilots complaining about the continual small amplitude upsets.

Comparisons of pilot activity and bank angle excursions for these four variations of roll damping with optimum $L_{\delta as}$ are shown in Figure III-6. Inspection of the δ_a traces shows that indeed the smallest inputs were for the $\tau_{rm} = .25$ sec case (III-6b); by comparison the $\tau_{rm} = .1$ sec case (III-6a) shows generally rougher control action, many small, sharp inputs, a few large ones, reflecting the pilots' working on the turbulence upsets; the 0.5 sec case (III-6c) is much like the .25 sec one, perhaps a little larger and more abrupt; finally, the $\tau_{rm} = 1.0$ sec trace (III-6d) shows the large, abrupt inputs commented upon previously.

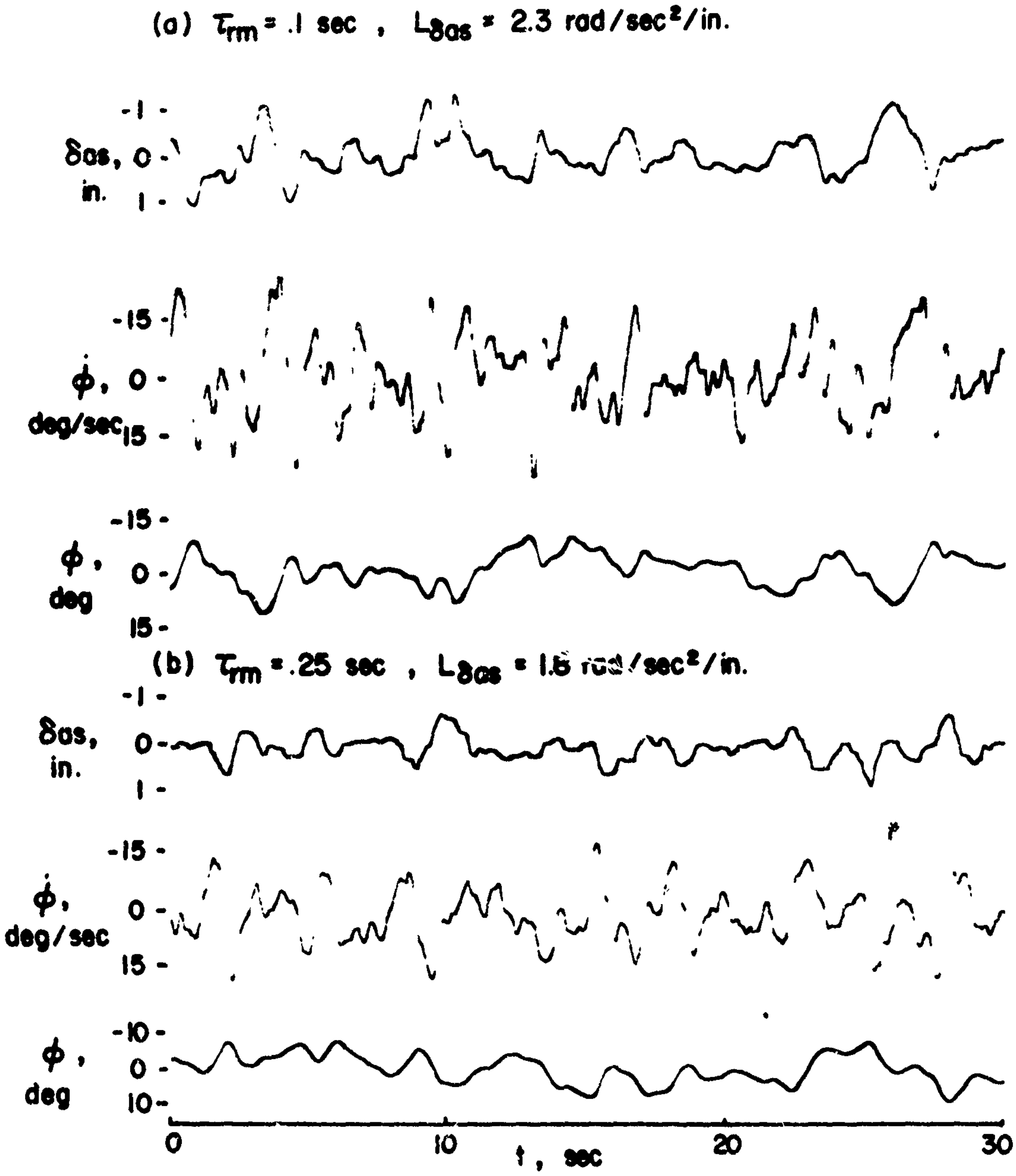


FIGURE III-6 EFFECTS OF ROLL DAMPING WITH $L_{\delta a}$ NEAR OPTIMUM. STICK CONTROL, $\delta as, \dot{\phi}$ AND ϕ VS TIME

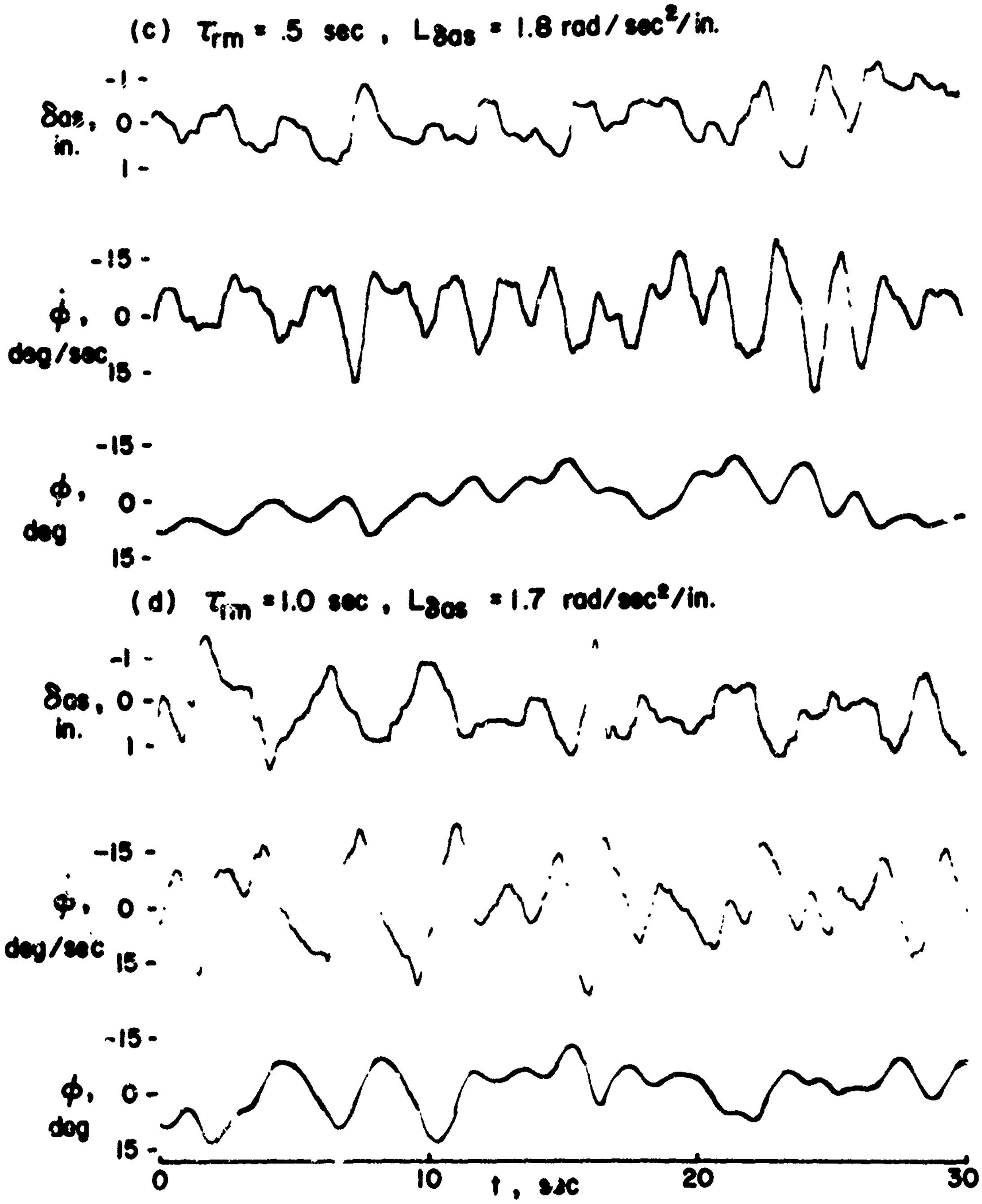


FIGURE III - 6 Concluded

The roll angle and roll rate time histories show a change in character as well as amplitude: many small, sharp $\dot{\varphi}$ peaks for the $\tau_{rm} = .1$ sec case - the turbulence "chatter" complained about - with bank angle excursions up to $\pm 15^{\circ}$; for the $\tau_{rm} = .25$ sec case, there was still considerable $\dot{\varphi}$ activity but smaller bank angle excursions. The traces for $\tau_{rm} = 0.5$ and 1.0 sec show few of the small, high frequency peaks, indicating a lessening of the L_p-related turbulence problem; $\dot{\varphi}$ and φ amplitude remain large, however, because of the "looseness" in roll, and occasional periods of $\pm 15^{\circ}$ wing-rocking may be noted.

Combined Effects - Roll Control Sensitivity and Roll Mode Time Constant

The discussion thus far has dealt with the effects of independent changes in $L_{\delta a}$ and τ_{rm}. Turning now to the combined effects of these two parameters, we find that there is no sharply defined "optimum" combination. This is indicated in Figure III-7 for the stick controller and in Figure III-8 for the wheel, which were obtained by cross-plotting the faired curves of Figures III-1 and III-2.

Although the plots are centered about $\tau_{rm} = .25$ sec (and $L_{\delta as} \doteq 2$ rad/sec^2/in for the stick and $L_{\delta aw} \doteq 6$ rad/sec^2/rad for the wheel), the boundaries are not closely spaced, indicating only a gradual degradation of flying qualities over a rather wide range of the two parameters. The fact that the rating contours in the "good" region are more oval and apparently more vertically oriented for the stick than those for the wheel is not considered to be significant but simply a consequence of $L_{\delta as}$ and $L_{\delta aw}$ not being numerically comparable.*

Moving away from the "best" values of τ_{rm} and $L_{\delta a}$ to the outer contours of Figures III-7 and -8, the results suggest that various segments of the plot might well be identified as in Figure III-9.

*Relabeling the $L_{\delta aw}$ axis in terms of rad/sec^2 per inch of linear motion at the rim of the wheel places the "best" level of sensitivity at $L_{\delta aw} = 1.2$. In terms of force applied in the appropriate direction, the optimum sensitivity for the $\tau_{rm} = .25$ sec case becomes $L_{\delta as} = .5$ rad/sec^2/ lb for both the stick and the wheel. However, more work, with force gradients different from the fixed ones used in these experiments, is required before concluding that this is the preferred level for both controllers.

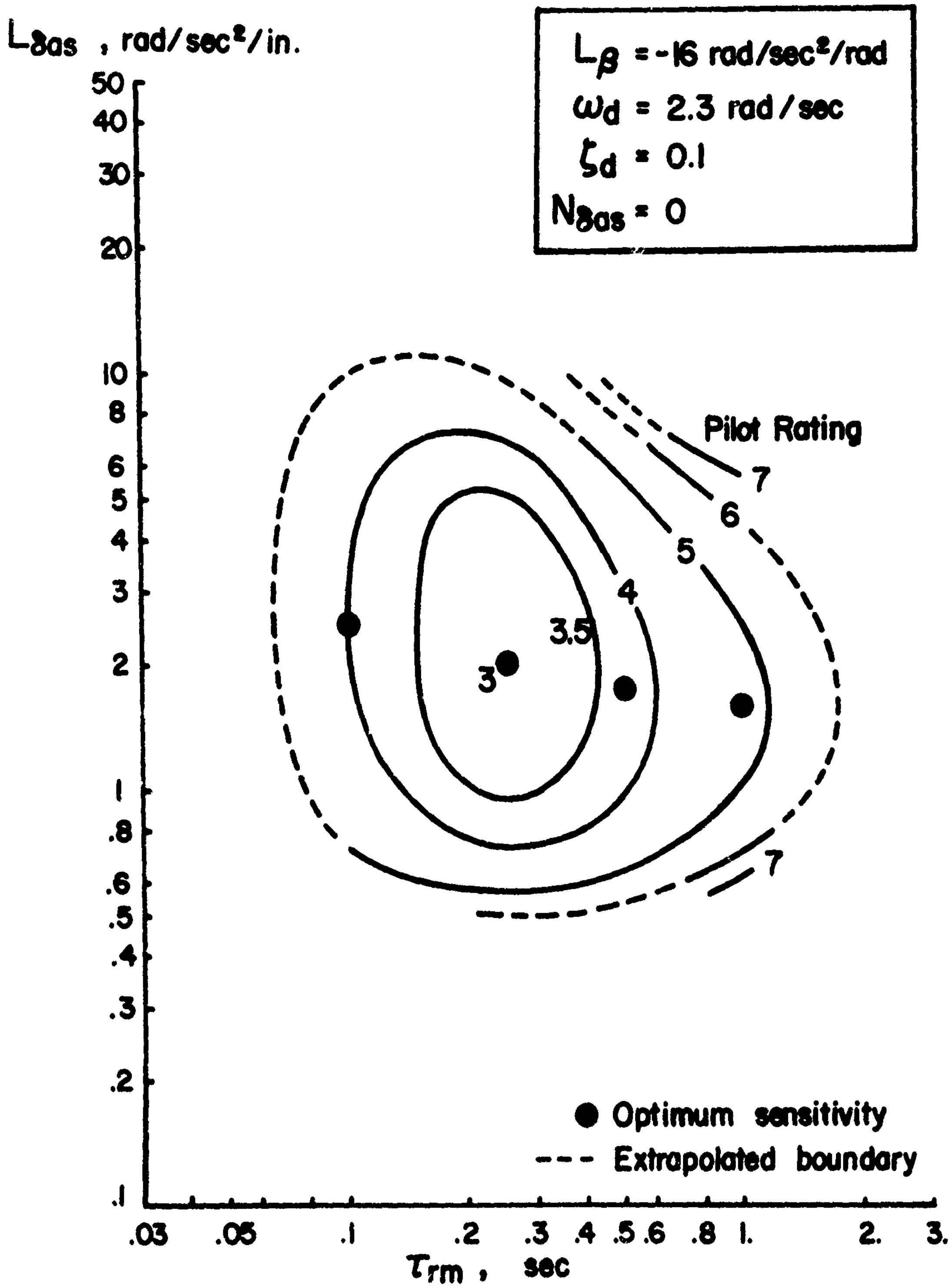


FIGURE III-7 PILOT RATING AS A FUNCTION OF CONTROL SENSITIVITY AND ROLL DAMPING, $L_{\delta as}$ VS τ_{rm}. STICK CONTROL.

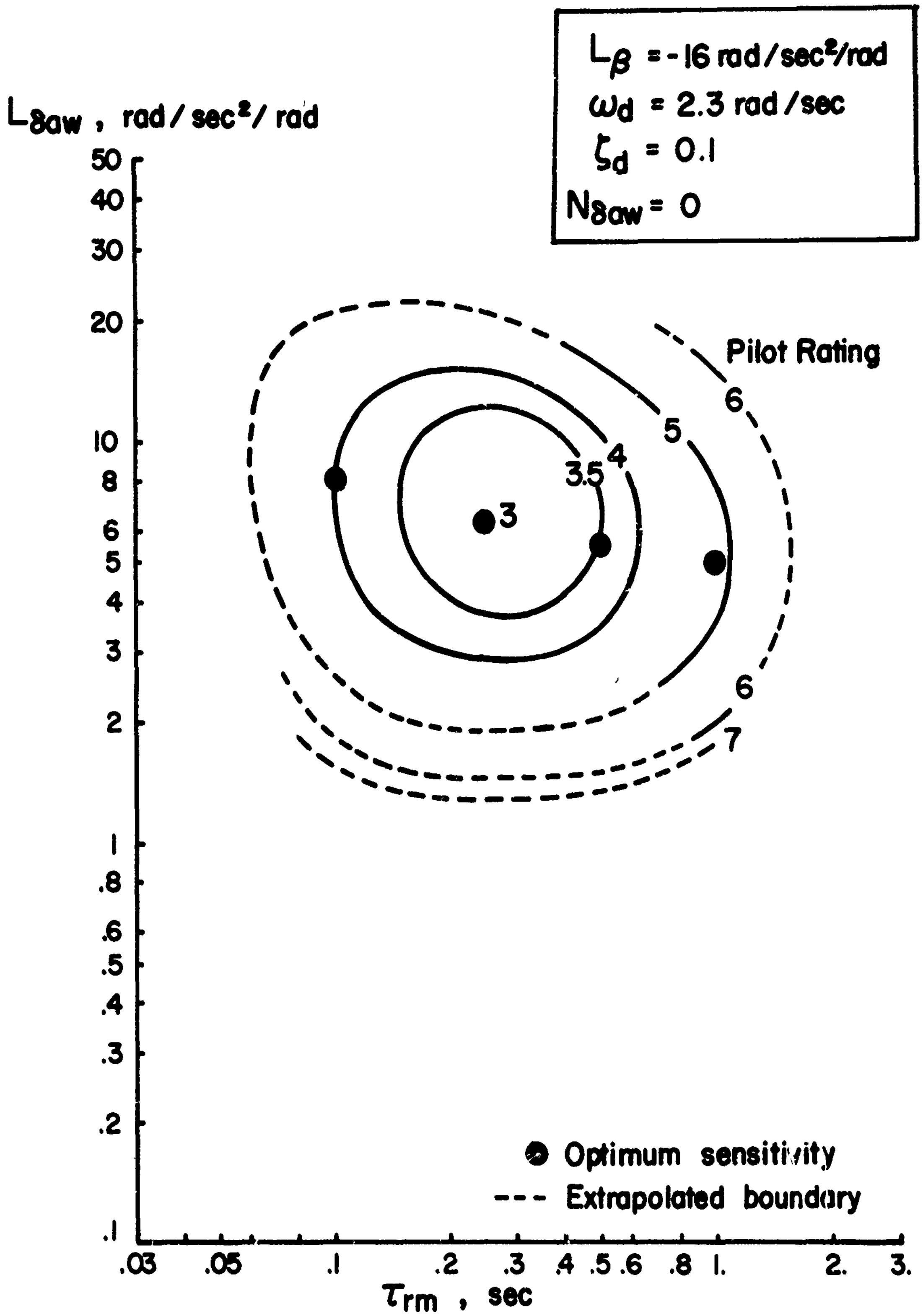


FIGURE III-8 PILOT RATING AS A FUNCTION OF ROLL CONTROL SENSITIVITY AND ROLL DAMPING, $L_{\delta aw}$ VS τ_{rm}. WHEEL CONTROL.

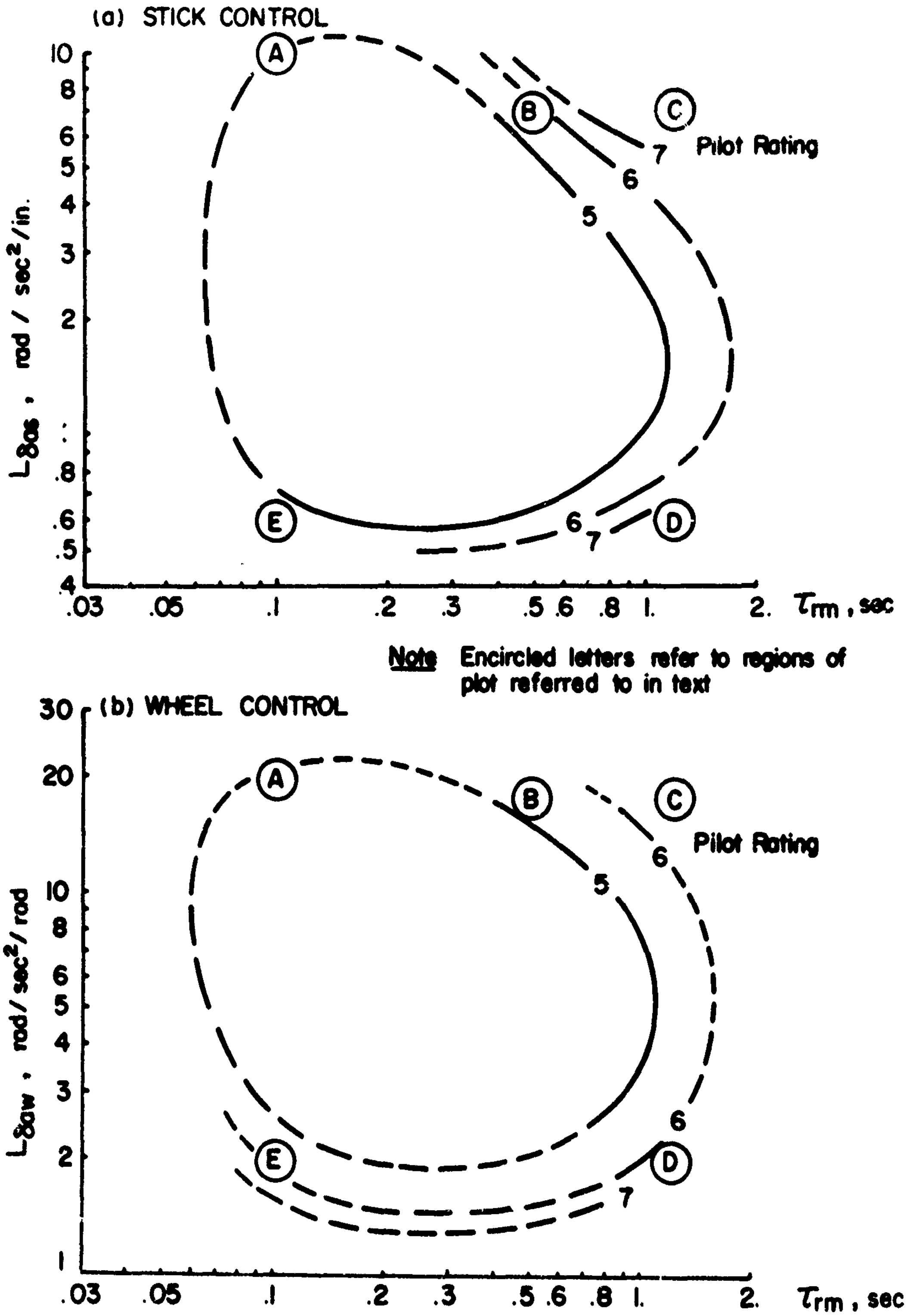


FIGURE III-9 COMBINED EFFECTS OF CONTROL SENSITIVITY AND ROLL DAMPING, $L_{\delta a}$ VS τ_{rm}

Region A identifies the case of high roll damping and high sensitivity. At least to the levels of $L_{\delta a}$ tested, the sensitivity itself caused no particular problem; the commentary associated with $\tau_{rm} = 0.1$, $L_{\delta as} = 7$, for example, noted that the ride was annoying and the sensitivity, though high, did not lead to any PIO tendencies. Thus the degrading feature is still the turbulence-caused roll upsets, and increasing sensitivity has neither helped nor hurt the situation.

The commentary on these high roll damping, moderate-to-high $L_{\delta a}$ configurations is interestingly devoid of remarks pertaining to roll dynamics or roll performance, although perhaps this should not be surprising. The precision of control would be very good due to the damping, and for the $L_{\delta as} = 7$ case just mentioned, the bank angle achieved in one second following a near-step stick input (0.2 sec allowed to complete the control input) would be about 35° per inch of deflection, apparently more than adequate for the ILS approach situation.

The plots indicate that the airplane of area "A" could be improved by simultaneously lowering $L_{\delta a}$ and increasing τ_{rm}, which would be the physical result, for example, of an increase in the rolling moment of inertia.

In the area of Figure III-9 labeled "B" the problem is primarily excessive control sensitivity, with a deficiency in roll damping just beginning to be a factor. For $L_{\delta as} = 7$, $\tau_{rm} = 0.5$ sec, pilot-induced wing rocking was evident for the entire approach, and the commentary noted that a deliberate effort had to be made to keep control inputs very small.

The rating contours in this region conform closely with lines of steady-state roll rate per unit of control deflection, as shown in Figure III-10 for the stick and Figure III-11 for the wheel: the 5.0 rating boundary is seen to be at about the $P_{ss}/\text{in} = 150^{\circ}/\text{sec}$ level for the stick and slightly more than $P_{ss}/\text{rad} = 400^{\circ}/\text{sec}$ for the wheel. This sort of roll capability is clearly neither needed nor desirable either for instrument flight or the visual lineup maneuver.

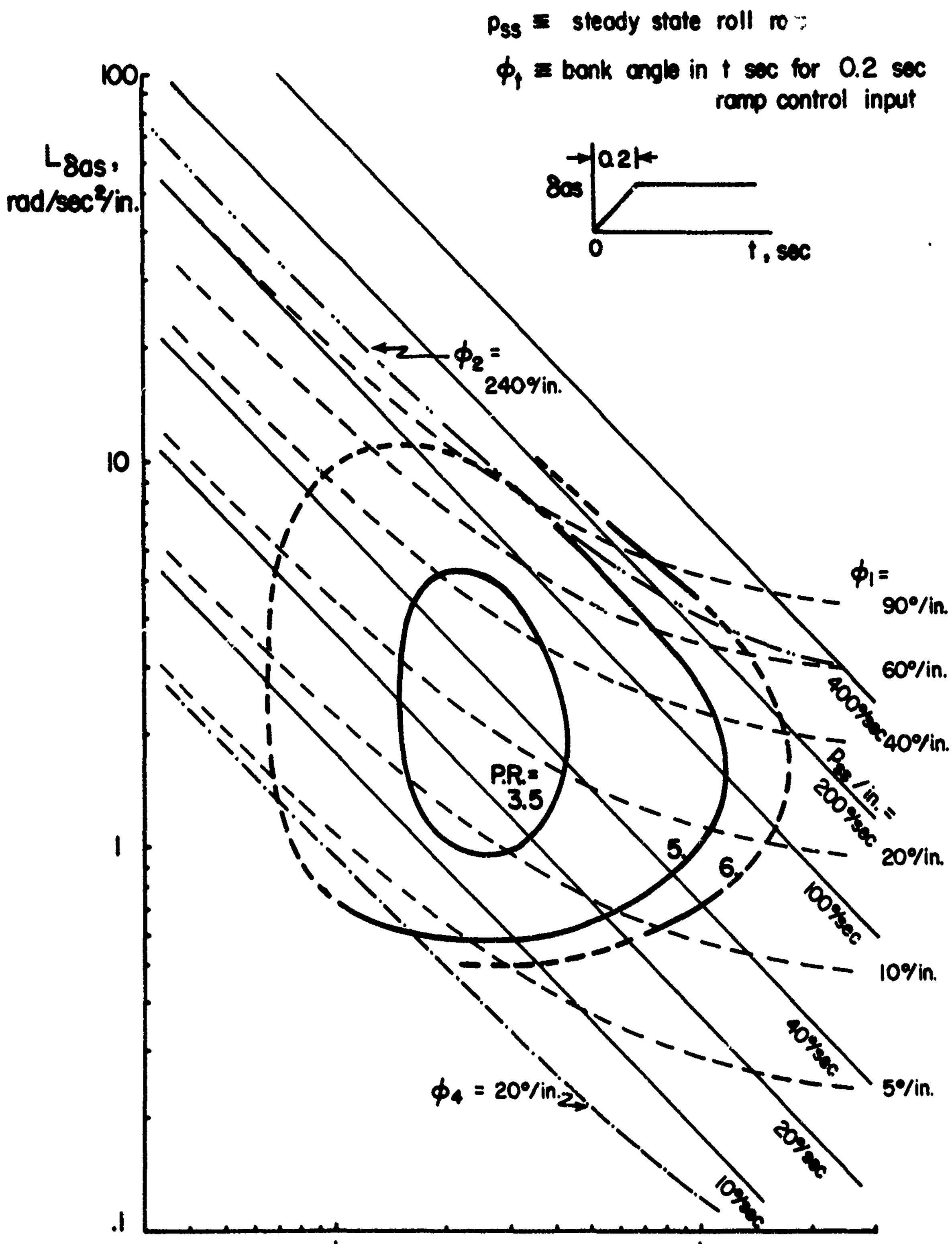


FIGURE III-10 ROLL PERFORMANCE AS A FUNCTION OF ROLL CONTROL SENSITIVITY AND ROLL DAMPING, $L_{\delta as}$ VS τ_{rm}. STICK CONTROL.

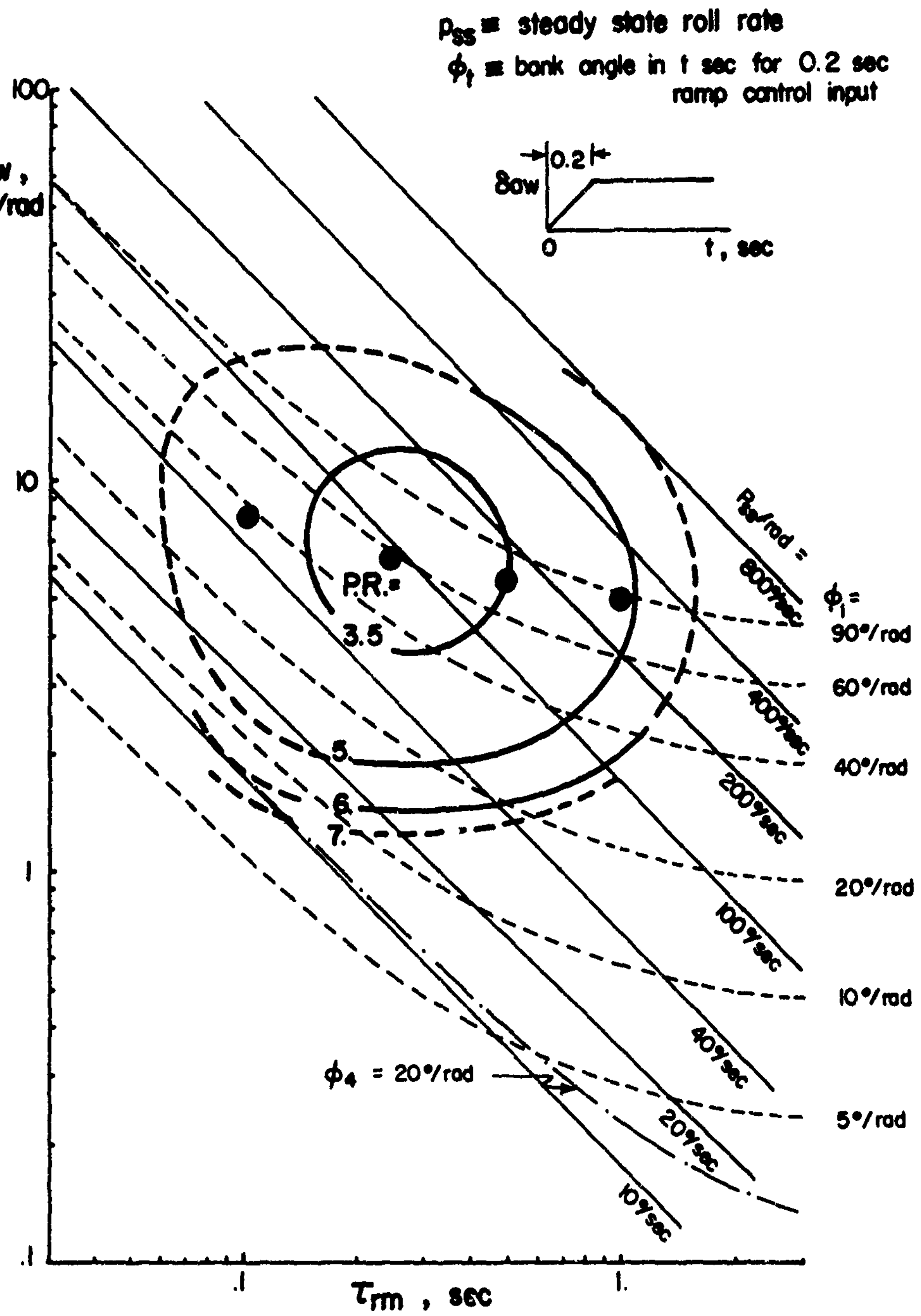


FIGURE III-11 ROLL PERFORMANCE AS A FUNCTION OF ROLL SENSITIVITY AND ROLL DAMPING, $L_{\delta aw}$ VS τ_{rm}. WHEEL CONTROL.

The "C" region of Figure III-9 represents configurations with high control sensitivity and low roll damping, with the latter now becoming of prime importance. With these low levels of roll damping anything above $L_{\delta as} = 2$ is described as "high sensitivity," leading to overcontrolling and difficulty with roll attitude. With $L_{\delta as} = 2.75$ and $\tau_{rm} = 1.0$ sec, the airplane was "touchy" and the pilot was "...trying to stay off the stick." At $L_{\delta as} = 3.5$ rad/ sec^2 / in precise control of bank angle was impossible while on instruments. At $L_{\delta as} = 5.6$ the sensitivity was so high that the roll PIO could only be stopped by a concerted effort to minimize control inputs - inadvertent inputs from arm and upper body inertia were a problem. The task performance was adequate, but the compensation was judged to be the maximum tolerable.

A portion of an approach with $\tau_{rm} = 1.0$ sec and $L_{\delta as} = 5.6$ rad/ sec^2 / in is shown in Figure III-12. By comparison with the $\tau_{rm} = 1.0$ sec, $L_{\delta as} \doteq 1.2$ run shown previously in Figure III-6, the control inputs are seen to be smaller, but the bank angle excursions are larger - all in all a difficult piloting problem.

The combination of low roll damping and low control sensitivity is found in the region labeled "D" in Figure III-9. The commentary notes that the low sensitivity was a severe problem, with the roll control stops being reached several times. The approach could be completed but the situation was highly objectionable.

The same pilot changed his technique on a different run with the same configuration and rated it about 2 units better. The basis for this is found in his commentary, which indicates that he was using large rudder inputs to counter the roll upsets, taking advantage of the large dihedral [$L_\beta = -16$].

The portions of flight record which illustrate this situation, Figure III-13, clearly show very high stick activity and low rudder activity for the first case, and, by comparison, smaller stick motions and larger rudder motions for the second. This change of technique would not be so successful, of course, if either the dihedral were less or the pilot not so skillful in use of the rudder.

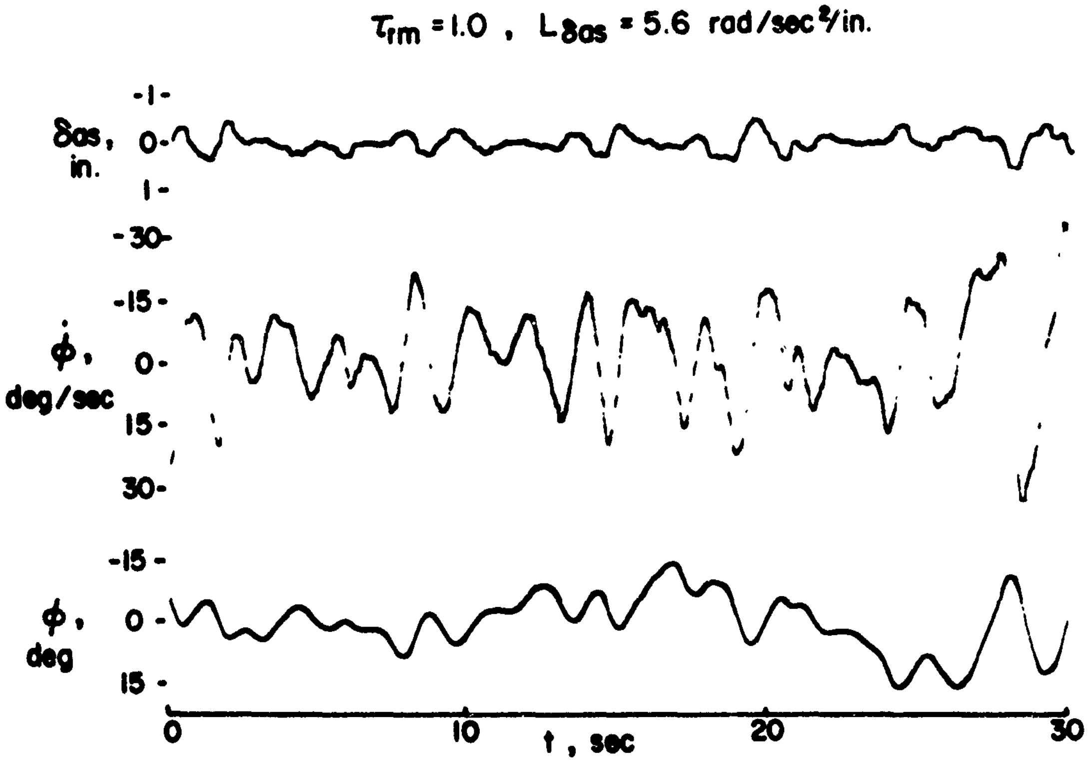


FIGURE III-12 EFFECTS OF COMBINED HIGH ROLL SENSITIVITY AND LOW ROLL DAMPING, δ_{as}, $\dot{\phi}$ AND ϕ VS TIME

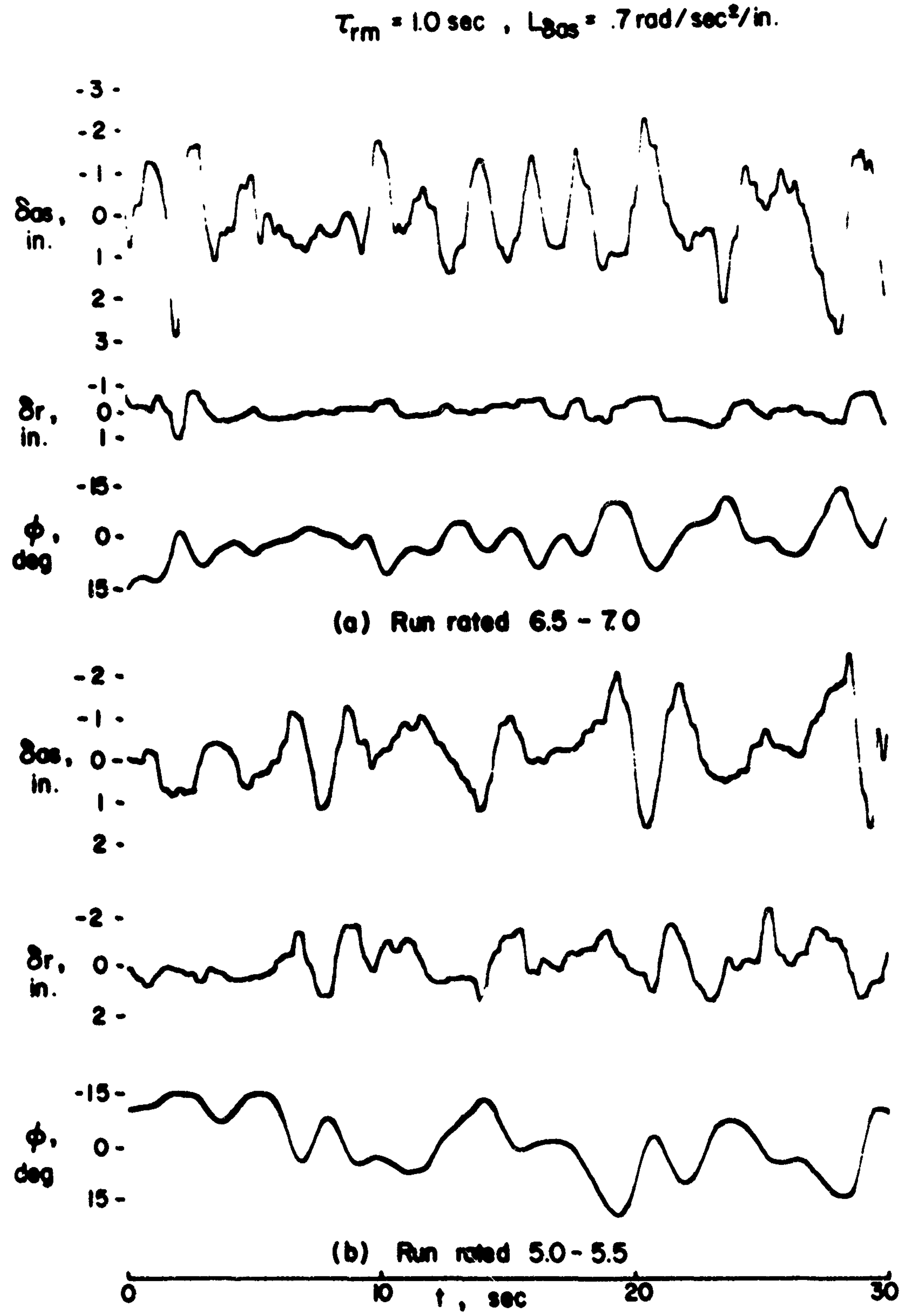


FIGURE III - 13 EFFECTS OF COMBINED LOW ROLL SENSITIVITY AND LOW ROLL DAMPING , δas , δr AND φ VS TIME

It should be noted that the roll performance per se is still quite high for these low damping, low control sensitivity configurations - p_{ss}/in is between 30 and 40 degrees per second, and ϕ_1 is in the neighborhood of 10^{o}/in for the stick control (see Figure III-10). This sort of performance is within the 3.5 rating boundary for τ_{rm} = .25 sec, so clearly the problem here is with the "looseness" and lack of precision in roll.

The remaining region of Figure III-10 to be discussed is that labeled "E," where the problems are associated primarily with low roll control power, not with roll damping. The roughly horizontal orientation of these lower rating contours suggests that for the range of "good" roll damping, τ_{rm} = 1.5 to .5 sec, the pilot needs at least some minimum level of available roll acceleration - $L_{\delta a} \delta a_{max} \geq 1\frac{1}{2}$ appears to be a reasonable limit - in order to fly the approach successfully, though perhaps not happily.

For the τ_{rm} = 0.1 sec, $L_{\delta as}$ = 0.7 rad/sec^2/in airplane, for example, the pilot complained as usual about the continuous small amplitude turbulence upsets associated with the large L_p, but more so about the very low roll control power. Here, too, he used rudder to augment the roll control.

In this area (E) the high roll damping does have the beneficial effect of preventing large sudden wing drops; thus as long as maneuvering requirements are small, as they are on the instrument segment of the approach, low control power is not too bothersome. However, it may be quite deficient for the offset maneuver. For the wheel controller with τ_{rm} = 0.1 sec and $L_{\delta aw}$ = 2.8 rad/sec^2/rad (control power $\doteq$ 4.4 rad/sec^2 for full wheel throw), the flight records show frequent very large inputs, and a stop-to-stop control movement while doing the visual runway lineup.

Comparison with Other Data

The data most directly comparable with the results just presented are those of Reference 4 which covered nearly the same range of sensitivity and damping. The simulator was, in fact, the same, but only the center stick controller was used. The most fundamental differences between the two tests involve the task and the pilots: The task of Reference 4 was a VFR precision approach using an optical glide slope, and Navy test pilots were asked to evaluate the various configurations as to their suitability for aircraft carrier operations. As previously noted, the present tests involved an ILS approach with visual runway lineup from an offset position, and civilian test pilots were asked to determine whether or not the configurations were suitable as small general aviation airplanes in the landing approach.

Secondary differences to be noted are the lower dihedral (L_β = -8 vs L_β = -16) and smaller directional stability (ω_d = 1.8 vs ω_d = 2.3) of the Navy tests. In both cases the Dutch roll damping ratio was the same at ζ_d = 0.1, and neutral (or near neutral) spiral modes were retained. Dutch roll excitation was nearly zero in both cases.

The τ_{rm} - $L_{\delta as}$ results from the two programs are superimposed in Figure III-14; although the rating boundaries don't in general coincide, the "best" combination of damping and sensitivity is nearly the same, and the optimum $L_{\delta as}$ values are quite close together especially for large τ_{rm}.

The present tests show a greater tolerance for high roll control sensitivity in the middle range of roll damping and for low control power in the high roll damping range. These trends both result most likely from the differences between visual and instrument operation. The comment was made several times that although the sensitivity or lack of it might be noticed during the "feel-out" portion of the run prior to intercepting the localizer, once established on the approach one isn't particularly aware of it unless it is extremely high or very low. Apparently degradations in roll control are more easily perceived if bank angle and roll rate cues are obtained continually from outside-the-cockpit references rather than from an intermittant scan of a 3-inch gyro horizon. Also, the pilots of Reference 4 were very anxious to avoid a wing-low touchdown for fear of landing gear damage in arrested

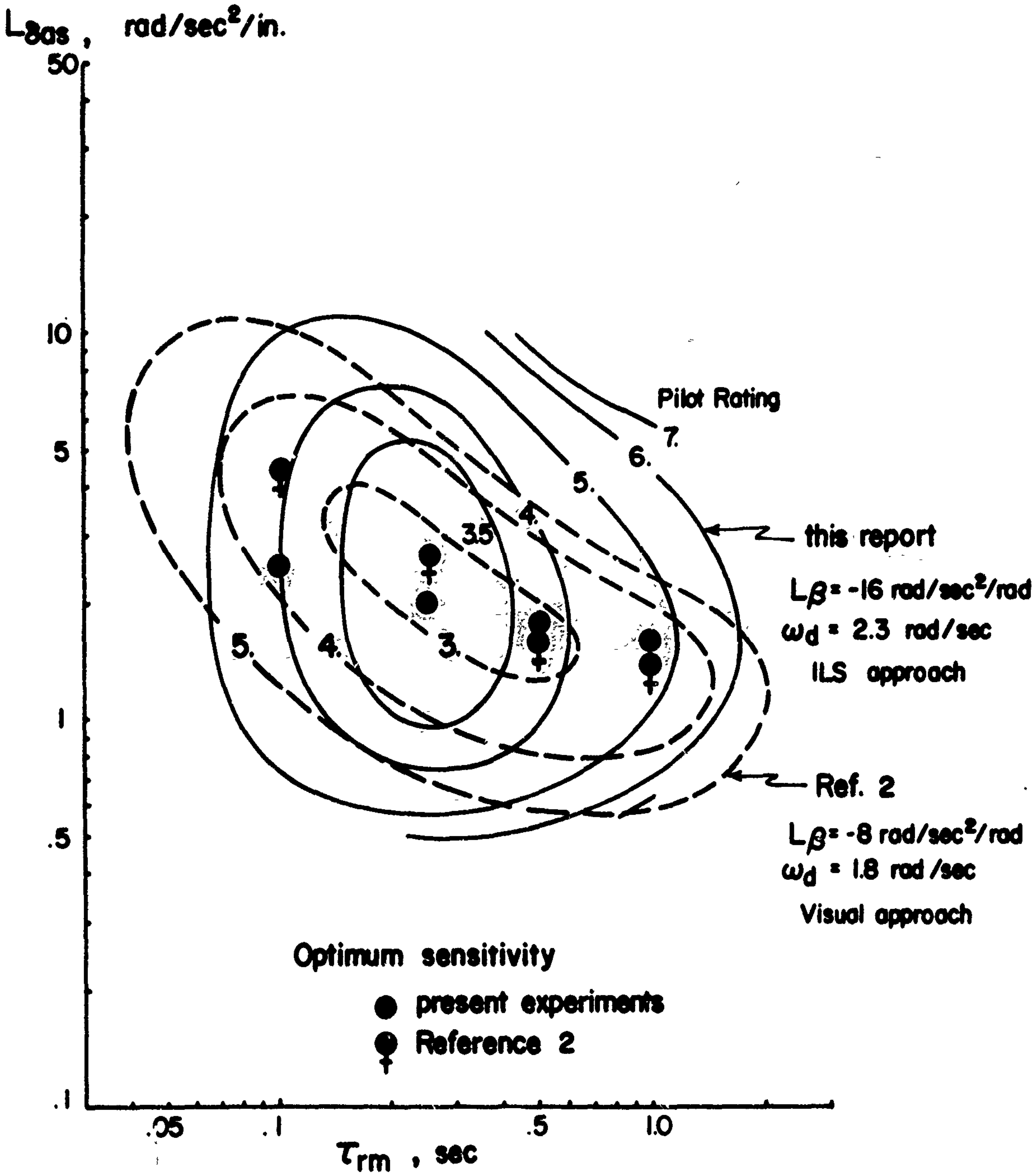


FIGURE III - 14 COMPARISON OF RESULTS WITH THOSE OF REFERENCE 4 , $L_{\delta as}$ VS τ_{rm} .

landings and this was a factor in their ratings; as far as the commentary indicates, the pilots of the present tests were not concerned over the possibility of a slightly wing-low touchdown.

Given a good controller, the pilots of Reference 4 will accept considerably higher roll damping than those of the present tests. Since the problem here is annoyance with the turbulence response associated with large L_p, it might be expected that the better cues available in the visual approach would permit the pilot to easily and continually keep the disturbances to a nondistracting level out to somewhat higher levels of roll damping.

Finally, one may note that the Reference 4 pilots were much more tolerant of low roll damping, a rating difference of about 1-1/2 units appearing at τ_{rm} = 1.0 sec. Although here again the better φ and $\dot{\varphi}$ cues are likely to permit better control of these very "loose" airplanes, another factor must be accounted for; namely, the difference in dihedral effect for the two experiments. With this level of roll damping the pilot has trouble coping with turbulence-related upsets, and here the rolling moments are almost entirely associated with L_β, since L_p is now quite small. Thus the pilots in the IFR tests were experiencing turbulence-caused roll accelerations of about twice the magnitude of the Reference 4 pilots, undoubtedly a factor in their lower ratings.

Some appreciation of the rating decrement due to the dihedral can be obtained from Figure 16 of Reference 11 which is reproduced here as Figure III-15. This indicates that the L_β = -16 of the present tests was near-optimum for the higher roll damping cases (τ_{rm} = .1 to .25), but could cause the ratings to fall to about 4.0 at τ_{rm} = 1.0 sec; reducing L_β to -8 might improve the present τ_{rm} = 1.0 sec ratings as much as one unit, which would make them quite close to the Reference 11 ratings in this region.

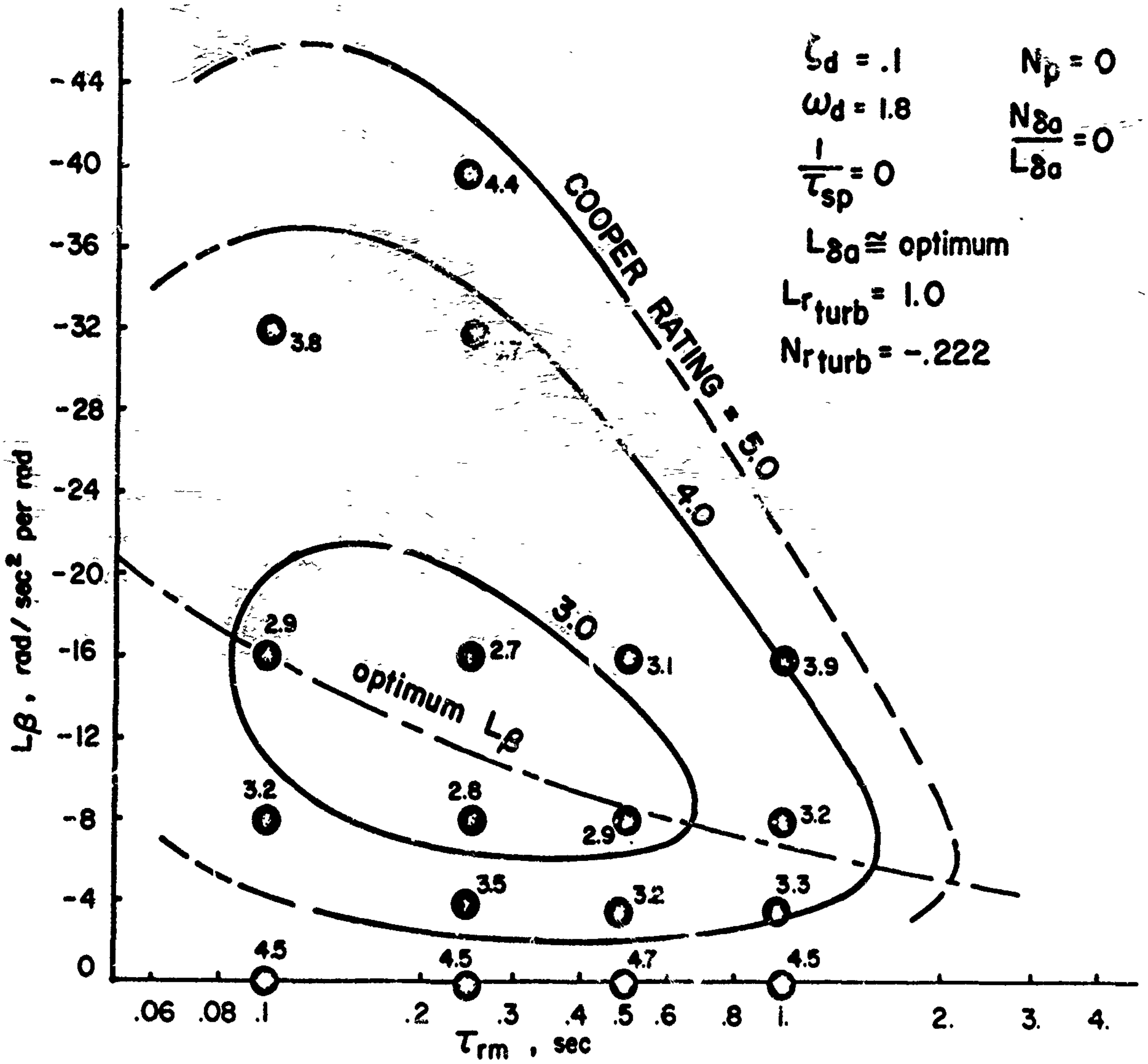


FIGURE III-15 EFFECT OF NON-OPTIMUM DIHEDRAL
(FIGURE 16 OF REFERENCE 11)

To summarize this point: the low tolerance for poor roll damping exhibited in these tests can be attributed in part to larger-than-optimum dihedral; even given lower dihedral though, these airplanes should remain harder to fly IFR than VFR.

Comparison with Military Specification Requirements

It is pointed out in the background document for the newly revised specification for piloted military airplane flying qualities (References 8 and 13 respectively), that in the large body of literature which treats the subject of roll control, there is very little which is directly related to small airplanes in the landing approach (Class I Airplanes - light utility, primary trainer, light observation; Flight Phase Category C - terminal flight phases). Nonetheless, specifications for this case have been established, based upon interpolation and extrapolation of existing data, stressing the fact that these airplanes are more closely related to fighters than to bombers or transports in their maneuverability requirements and response to turbulence.

Roll mode time constant requirement. This requirement, aimed at providing precision of control, calls for maximum roll mode time constants of τ_{rm} = 1.0 sec for Level 1,* 1.4 sec for Level 2,** and 10 sec for Level 3*** for landing approach.

The present tests show the Level 1 rating to be reached at $\tau_{rm} \doteq .5$ sec assuming optimum control sensitivity. It will be recalled from the discussion in the preceding section that if lower dihedral had been used, the 3.5 rating boundary would probably have been closer to the τ_{rm} = 1.0 sec line, and thus in closer agreement with the requirement. It would appear, though, that this

---

*Level 1 corresponds to Cooper-Harper Rating 1-3.5; clearly adequate for the mission Flight Phase.

**Level 2 corresponds to Cooper-Harper Rating 3.5-6.5; adequate for mission Flight Phase, but with increased workload or degradation of effectiveness.

***Level 3 corresponds to Cooper-Harper Rating 6.5-9; airplane is controllable but workload is excessive or mission effectiveness inadequate or both. Terminal Flight Phase can be completed.

Level 1 requirement makes no allowance for the difficulties of the ILS approach or for unfavorable values of interacting parameters.

The Level 2 limit of $\tau_{rm} = 1.4$ sec tends to be more nearly confirmed by these results, although a small extrapolation beyond the longest time constant tested (1.0 sec) is involved. The quoted requirement would allow for a reasonable range of $L_{\delta a}$ about the optimum and for other unfavorable parameters.

The authors of Reference 8 state that the Level 3 limit of $\tau_{rm} = 10$ sec is relatively arbitrary; judging by the difficulties experienced with one-second time constants in these experiments it is difficult to imagine being able to complete an instrument approach in turbulence with such a machine.

Roll performance requirement. In Reference 13 the roll performance requirement is stated in terms of the time allowed for the airplane to bank through 30° following a control input which is completed in 0.2 sec. The nomenclature used is φ_t, or bank angle achieved in t seconds. Reference 8 indicates that because of the general lack of data for small airplanes, requirements were picked such that roll performance increases in equal multiples in going from very heavy (Class III) to medium (Class II), to light (Class I) to fighter (Class IV) aircraft; this was based on consideration of maneuvering requirements and response to atmospheric disturbances.

The requirements for Levels 1, 2, and 3 for small aircraft, fighters, and medium weight aircraft (paragraph 3.3.4.4 of Reference 8) are shown in Figure III-16 superimposed on the 3.5, 5, and 6 rating boundaries of the present tests.

The Class I, Level 1 limit of $\varphi_t = 30^{\circ}$ in 1.3 seconds is seen to be slightly outside of the 3.5 stick boundary and close to the 5.0 wheel boundary. The reasons for the difference between the stick and wheel are not fully known, but it may be noted that the control power for the wheel controller is based upon 90° of travel, an amount which is awkward to achieve with one hand without changing one's grip on the wheel. The flight records show that even when the

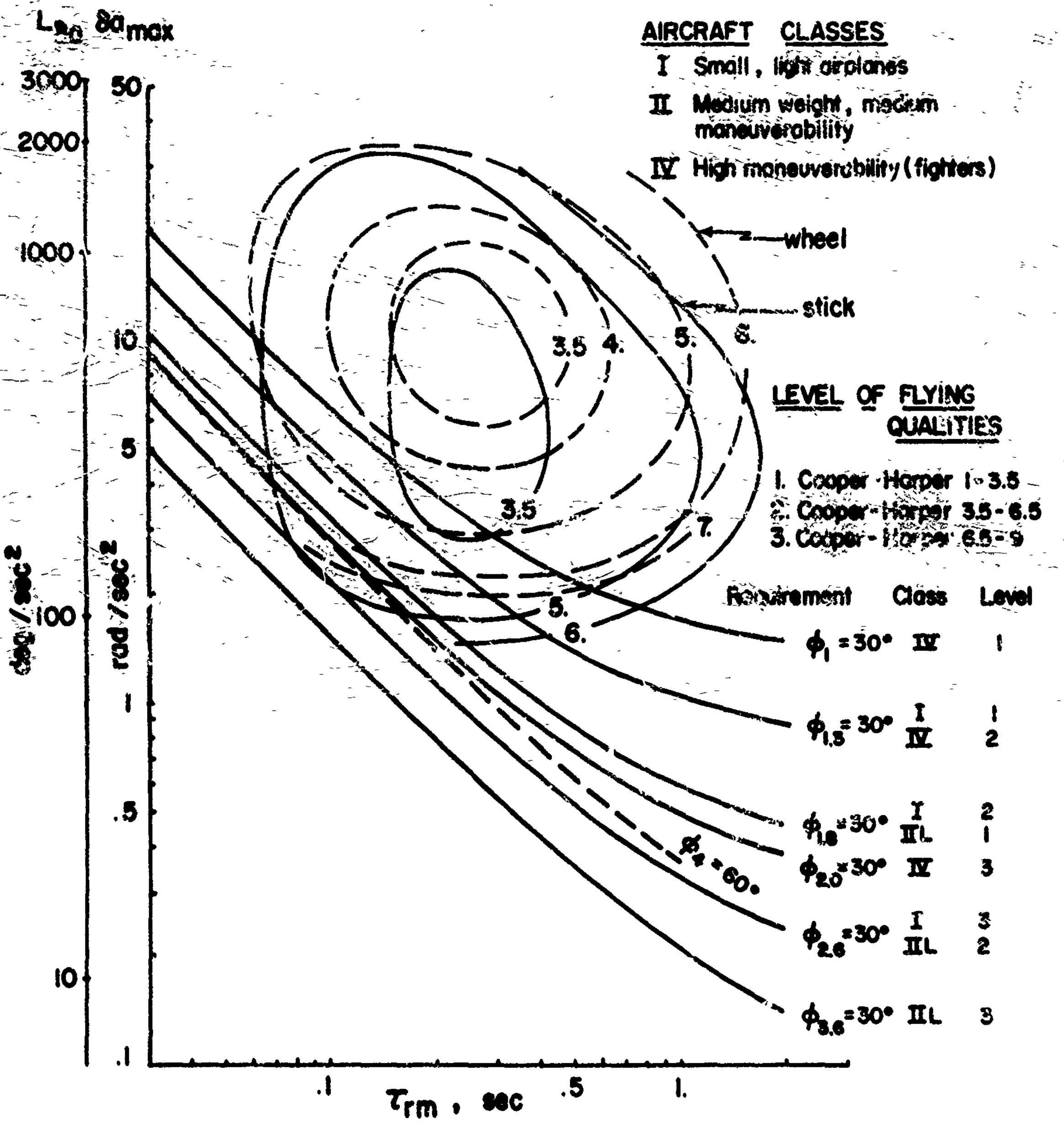


FIGURE III-16 ROLL PERFORMANCE, COMPARISON WITH MILITARY SPECIFICATION, REFERENCE 13, $L_{\delta a}\ \delta a_{max}$ VS τ_{rm}

pilot was complaining about low control power ($L_{\delta aw}$ = 2.7 rad/sec^2/rad, corresponding to $L_{\delta a}\,\Delta\delta_a$ = 4.25 on Figure III-16) he was using only about ±45^o of wheel throw for the τ_{rm} = .25 sec airplane. In other words the rating for that configuration would probably have been the same (4) even if the physical stops had been ±60^o instead of ±90^o. The lower edge of the 3.5 boundary would then be at about $L_{\delta a}\,\Delta\delta_{a_{max}}$ = 3 rad/sec^2, agreeing quite closely with the boundary for the stick.

At any rate, the Class I, Level 1 boundary would appear to be too lax, especially if the designer of a mechanical control system feels obliged to provide more cockpit control travel than is really useful in order to keep force gradients low; the Class IV, Level 1 requirement of φ_t = 30^o in one second fits the data better and there seems to be little reason not to make this the Class I, Level 1 requirement also.

There is one disturbing point here, however, and that is the fact that an airplane having a combination of minimum Level 1 roll damping (τ_{rm} = 1.0 sec) and minimum Level 1 roll performance (φ_t = 30^o in 1 second) will be a very poor handling airplane on instruments, particularly if it has moderate or large dihedral. The roll performance requirement, in other words, fits the data well only for roll mode time constants shorter than about τ_{rm} = 0.3 sec; beyond that, it appears that some lower limit on available roll acceleration - perhaps 3 rad/sec^2 - is needed for Level 1.

The Class I, Level 2 boundary of φ_t = 30^o in 1.8 sec is seen to be a little more restrictive than necessary at short roll mode time constants, and the Class IV, Level 3 requirement of φ_t = 30^o in 2.0 second would do as well. Another boundary which fits the short time constant situation is the φ_t = 60^o in 4 seconds requirement of the ARB (Reference 14, Chapter K2-5, Section 6.4.2).

As in the Level 1 case, these Level 2 roll performance requirements are not compatible with the maximum roll mode time constant allowed (τ_{rm} = 1.4 sec). An airplane with so little control power as to be definitely unsafe, if not unflyable, could easily meet the roll performance requirement if its roll damping were that low. A lower limit on available roll acceleration is indicated, perhaps $L_{\delta a}\,\Delta\delta a_{max} \geq 1.5$ rad/sec^2 for $\tau_{rm} \geq .15$ sec, although even this would be marginal at $\tau_{rm} = 1.0$ sec.

The Class I, Level 3 boundary corresponds to $\varphi_t = 30^{\circ}$ in 2.6 seconds, a value picked to provide about half the roll acceleration capability of the Level 2 requirement. This appears to be slightly restrictive for τ_{rm} less than .15 seconds but inadequate for larger ones. In view of the suggested relaxation of Level 2 to $\varphi_t = 30^{\circ}$ in 2.0 seconds for $\tau_{rm} \leq .15$ sec, the Level 3 boundary might well be placed at $\varphi_t = 30^{\circ}$ in 3.6 seconds, for $\tau_{rm} \leq .10$, with a minimum available roll acceleration requirement of 1.0 rad/sec^2 for $\tau_{rm} > .10$ sec.

To summarize, the suggested Class I, Flight Phase Category C requirement is the following:

Level 1: $\varphi_t = 30^{\circ}$ in 1 second, with $L_{\delta a}\,\delta a_{max} \geq 3$ rad/sec^2 if $\tau_{rm} > 0.3$ sec.

Level 2: $\varphi_t = 30^{\circ}$ in 2 seconds, with $L_{\delta a}\,\delta a_{max} \geq 1.5$ rad/sec^2 if $\tau_{rm} > .15$ sec.

Level 3: $\varphi_t = 30^{\circ}$ in 3.6 seconds, with $L_{\delta a}\,\delta a_{max} \geq 1.0$ rad/sec^2 if $\tau_{rm} > .10$ sec.

Roll control forces. Reference 9 specifies maximum roll control forces to meet the roll performance requirements as follows for the approach case:

Level	Maximum Stick Force, lb	Maximum Wheel Force, lb
1	20	20
2	20	20
3	35	70

The minimum forces specified are breakout force plus:

a. Level 1 --- one-fourth the above values

b. Level 2 --- one-eighth the above values

c. Level 3 --- zero

The maximum forces used in the experiment were well within the limits for all Levels, since full control throw required 12 lb for the stick and 17 lb for the wheel.

The minimum force requirement is getting at the matter of roll response sensitivity, φ_t/δ. This could be stated either in terms of displacement or force; Reference 8 indicates that force was chosen on the basis of recent (unspecified) experimental evidence for stick controllers. Although the present experiments don't definitely resolve the question either, it may be noted that pilots preferred the same level of sensitivity, $L_{\delta a}$, measured in rad/sec^2 per pound for both stick and wheel, whereas $L_{\delta a}$ in rad/sec^2 per inch or per radian showed no such correlation.

Figure III-10 indicates that in these tests the optimum roll response sensitivity corresponds roughly to $\varphi_1 = 20^\circ$/in or 5°/lb; the maximum acceptable for Level 1 corresponds to about $\varphi_1 = 40^\circ$/in or 10°/lb; and the maximum for Level 2 might be in the neighborhood of $\varphi_1 = 90^\circ$/in or 22.5°/lb although in this region lines of steady-state roll rate more nearly fit the curves than the constant φ_t lines. As mentioned immediately above, these values fit either stick or wheel controllers.

According to the requirement, the minimum forces are to be related to the roll performance requirements. Thus if the Level 1 requirement is $\varphi_t = 30^\circ$ in one second, and the sensitivity is the maximum acceptable for Level 1, that giving $\varphi_1 = 10^\circ$/lb, then the force to meet the requirement is

$$\frac{\varphi_1 = 30^\circ}{\varphi_1 = 10^\circ/\text{lb}} = 3 \text{ lb}$$

Actually, the stated Level 1 roll performance requirement is $\varphi_t = 30^\circ$ in 1.3 seconds, which is close to $\varphi_t = 22.5^\circ$ in one second, so the minimum force would be 2.25 lb. Similarly, the published Level 2 requirement is $\varphi_t = 30^\circ$ in 1.8 second, which is close to $\varphi_t = 15^\circ$ in one second in the region of good roll mode time constant, so the minimum force would be

$$\frac{\varphi_1 = 15^\circ}{\varphi_1 = 22.5^\circ / \text{lb}} = .67 \text{ lb}$$

Thus the experiments indicate that the requirements could be met with minimum forces much smaller than the 5 lb for Level 1 and 2.5 lb for Level 2. However, the requirement is not unreasonable, and if the actual roll response sensitivity were near the optimum of $\varphi_1 = 5^\circ$/ lb, then a $\varphi_t = 30^\circ$ in one second Level 1 requirement would require 6 lb and a $\varphi_t = 15^\circ$ in one second requirement would require 3 lb, both within the specification.

An additional, and governing, requirement for Class IV aircraft (fighters) in landing approach is that the roll response sensitivity shall not be greater than 7.5° in one second per pound for Level 1 and not greater than 12.5° in one second per pound for Level 2. The present experiments indicated that for an ILS approach 10° in one second per pound for Level 1 and a little over 20° in one second per pound could be tolerated.

Suggested Civil Criteria

The Federal Airworthiness Standards for this class of airplane are intended to provide a "minimum level of safety" for normally encountered operating conditions without requiring exceptional piloting skill, alertness, or strength. This concept of a minimum standard suggests requirements not necessarily the same as, but at least parallel in philosophy with the Level 2 requirements of Reference 13, which require flying qualities adequate to accomplish the mission flight phase, but with some degradation in mission performance and/or increase in pilot workload present.

Based on the preceding discussion of the experiments, the following requirements are suggested as being appropriate for small airplanes in the landing approach (including instrument approaches).

Roll mode time constant. The roll mode time constant should be no greater than 1.4 seconds. This provides some allowance for non-optimum control sensitivity and unfavorable values of other interacting factors such as dihedral effect. This is based upon the results presented in Figures III-7 and III-8 and the discussion accompanying Figure III-9. The discussion on page 50 is also pertinent.

Roll performance. The roll control power should be sufficient to provide $\varphi_t = 30^\circ$ in two seconds or 60° in four seconds for roll mode time constants up to $\tau_{rm} = .15$ sec. For time constants between .15 and 1.4 sec, the roll control should provide a roll acceleration capability of at least 1.5 rad/ sec^2. These are based upon the evidence of Figure III-16.

As previously discussed on page 55, the $\varphi_t = 30^\circ$ in two seconds requirement can be met with an unsafe low level of control power if the roll damping is low, hence the roll acceleration requirement.

Roll control forces. In meeting the roll performance requirement, the maximum control force should not exceed 20 lb for either stick or wheel. This is consistent with the military requirement.

The roll response sensitivity should not be greater than $\varphi_t = 60^\circ$ in two seconds per pound ($\varphi_t = 240^\circ$/ in). This is based upon the upper boundaries of the $L_{\delta a}$ vs τ_{rm} plots of Figures III-10 and III-11. It seems desirable to keep this φ_t requirement format which is perhaps physically more meaningful to the pilot and which covers roll responses which are affected by roll-sideslip coupling. It is also easier to test for than a steady-state roll rate requirement, for example.

Other considerations. There is some evidence here that wheel control throws of much more than $\pm 60^{\circ}$ are not really useable (discussed on page 54). However, it is appreciated that a mechanical control system may require larger angles in order to keep forces low. The Reference 13 compromise of no more than ± 80 degrees for completely mechanical systems seems appropriate as a requirement.

A lower limit on roll mode time constant is not suggested, even though the rating boundaries close on the left hand side. It will be recalled that the reason for the lower ratings here was the poor turbulence response associated with large L_p; this was sufficiently annoying to downgrade the configurations, but the damping itself helps keep the roll excursions small and it is not likely that safety would be compromised even at very small time constants. The ride qualities might be very poor, however.

IV. RESULTS AND DISCUSSION - DUTCH ROLL EXCITATION PARAMETERS

General Results

The averaged pilot ratings from the four participating pilots are shown in Figure IV-1, the upper plot being for $\omega_d = 2.3$ rad/sec and the lower for $\omega_d = 1.3$ rad/sec. The curves faired through these points are for nearly constant values of $\zeta_\varphi \omega_\varphi$, which, when cross-plotted, yield the constant-rating contours of Figure IV-2 for the higher Dutch roll frequency case and of Figure IV-3 for the lower frequency case.

These complex-plane plots are essentially similar in shape, showing in general the degrading effects of large Dutch roll excitation and the beneficial effects of having the zeros of the roll-to-aileron transfer function close to the Dutch roll natural frequency - that is, $\omega_\varphi / \omega_d$ should be near unity if ζ_φ is greater than ζ_d (also if ζ_φ is less than ζ_d, but this would require such large positive values for the normally negative N_p derivative that it seems an unlikely situation).

Aside from these general similarities, however, there are some important differences which must be examined: over most of the plot, including the regions very close to the Dutch roll poles, the $\omega_d = 1.3$ rad/sec airplane is rated about one unit lower than the $\omega_d = 2.3$ rad/sec airplane - the 5 boundary for the low frequency case, for example, is very nearly of the same shape and extent as the 4 boundary for the high frequency machine, and the configurations closest to the pole are rated about 4 and 3, respectively. Some of this difference for areas away from the poles can be charged to larger Dutch roll excitation for a given distance from the pole for the low-frequency case (see K_d / K_{ss} overlays for Figures IV-2 and IV-3), but the close-in configurations all had K_d / K_{ss} between 0.10 and 0.20.

The second notable difference between the two plots is the disposition of the region of best flying qualities with respect to the Dutch roll poles. For

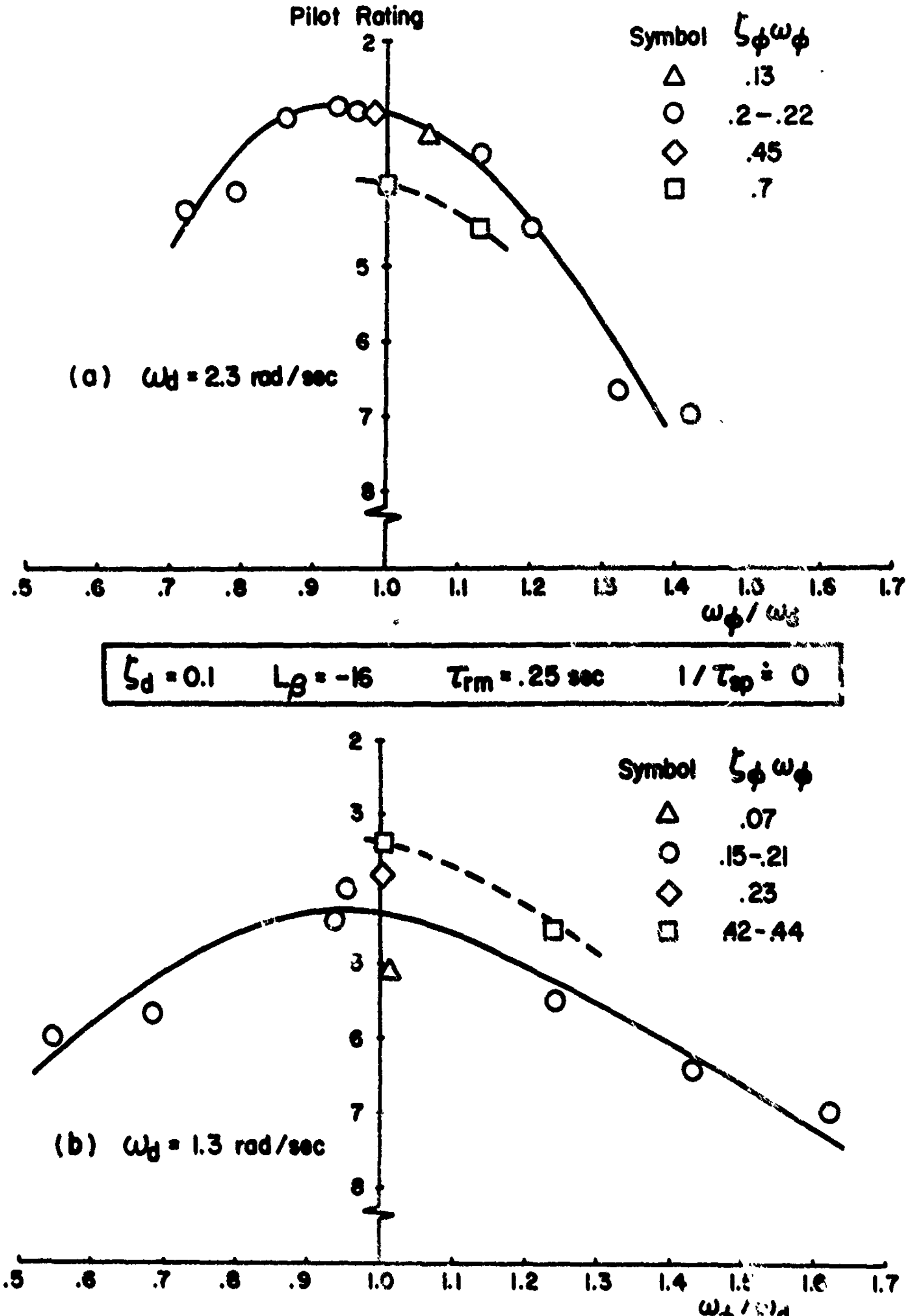
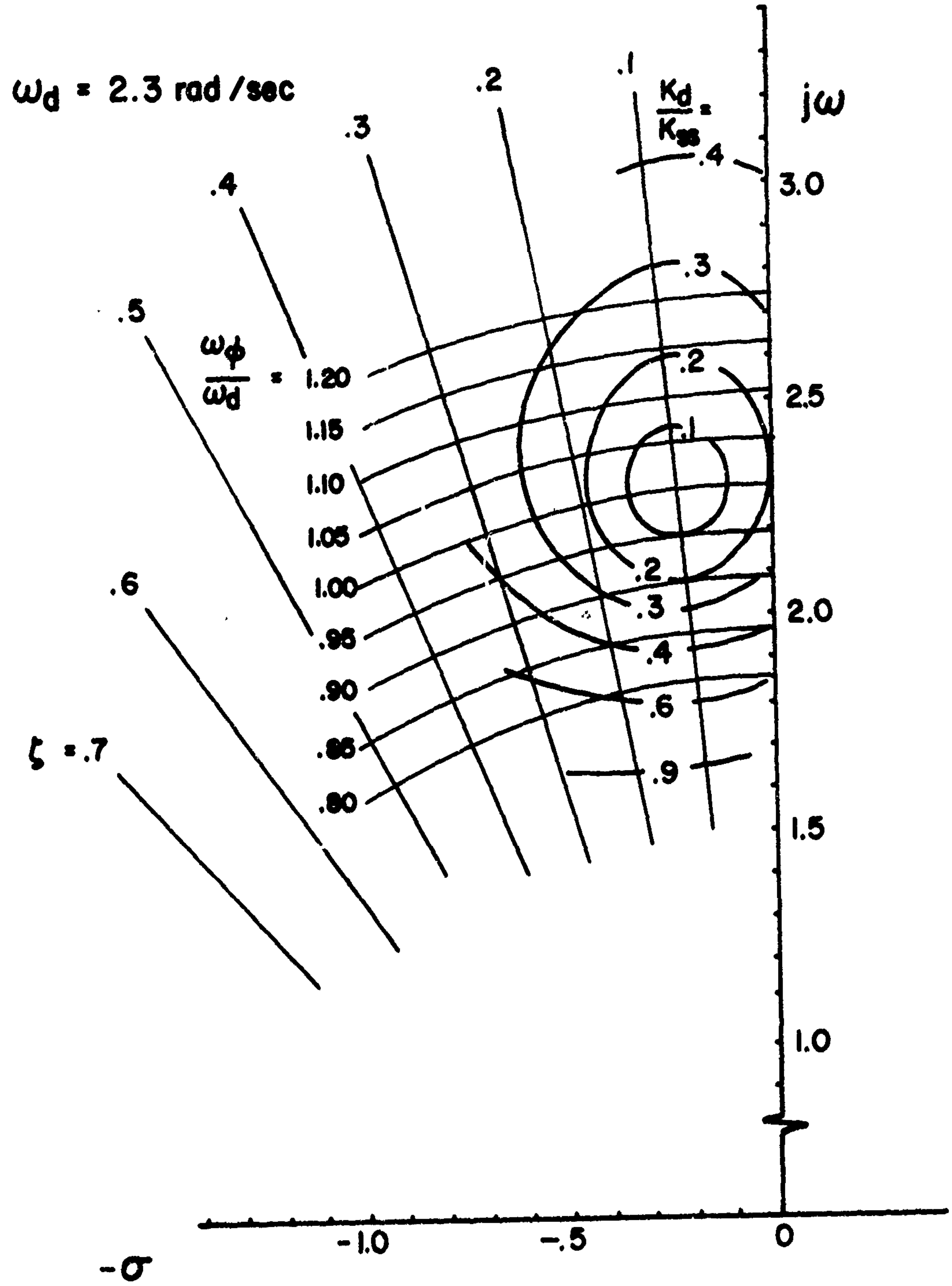


FIGURE IV-1 PILOT RATING AS A FUNCTION OF $\frac{\omega_\phi}{\omega_d}$, $\zeta_\phi \omega_\phi$ CONSTANT.
ω_d = 2.3 AND 1.3 RAD/SEC



ωd = 2.3 rad/sec
ωφ/ωd = 1.20
1.15
1.10
1.05
1.00
.95
.90
.85
.80
ζ = .7
.6
.5
.4
.3
.2
.1
Kd/Kss = .4
.3
.2
.1
.2
.3
.4
.6
.9
jω
3.0
2.5
2.0
1.5
1.0
-σ
-1.0
-.5
0

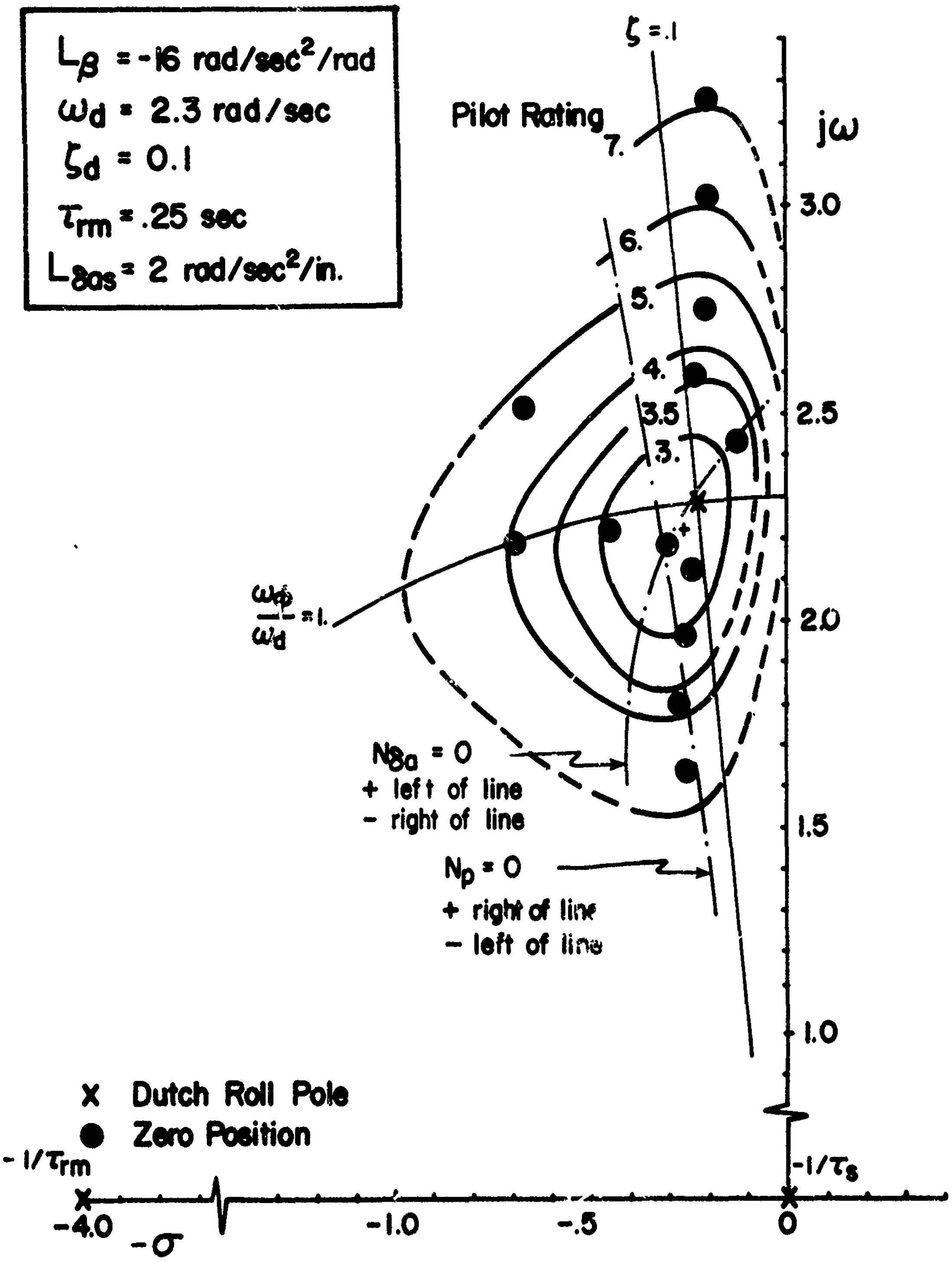
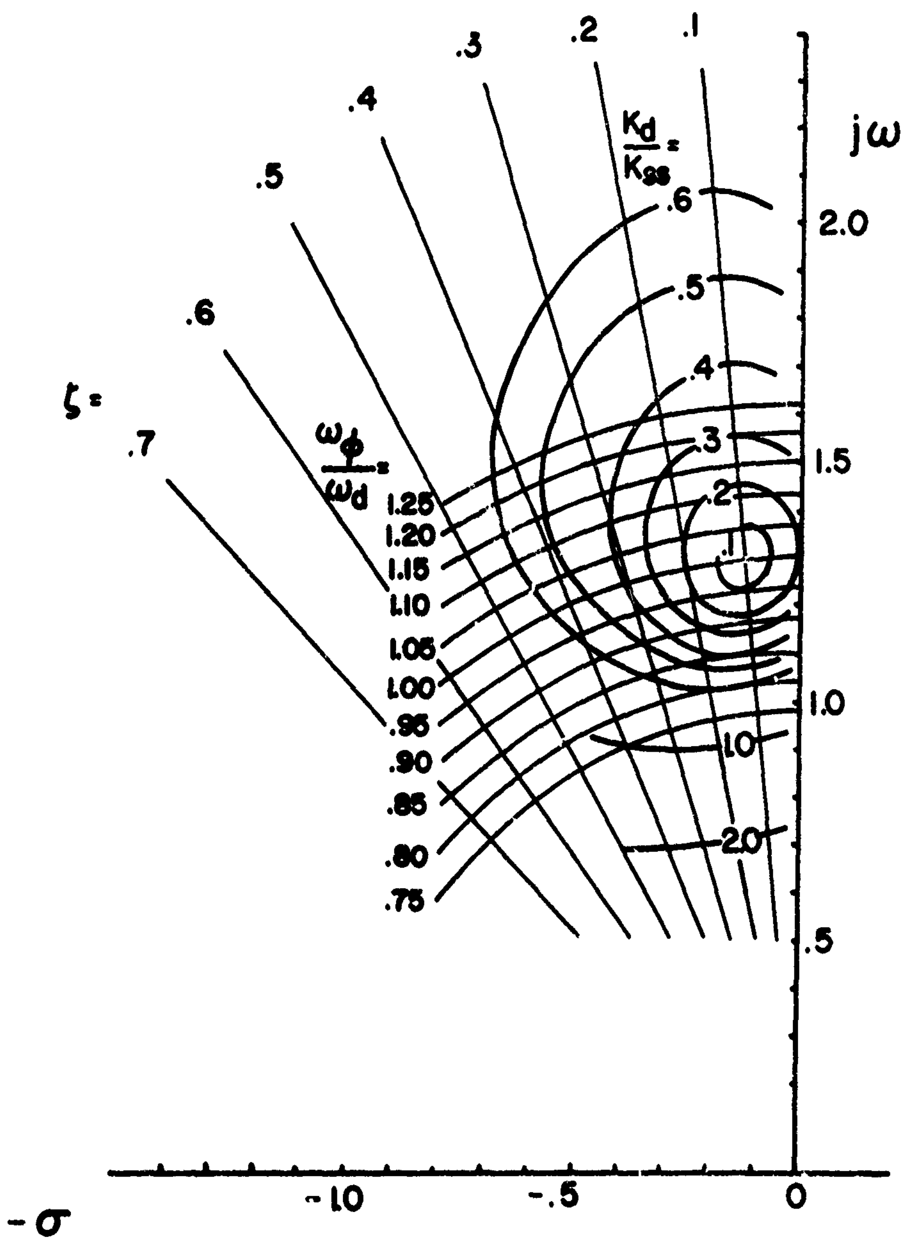


FIGURE IV-2 PILOT RATING CONTOURS AS A FUNCTION OF ROLL TRANSFER FUNCTION ZERO POSITION. ω_d = 2.3 RAD/SEC

ω_d = 1.3 rad/sec



L_β = -16 rad/sec²/rad
ω_d = 1.3 rad/sec
ζ_d = 0.1
τ_{rm} = .25 sec
$L_{\delta as}$ = 2 rad/sec²/in.

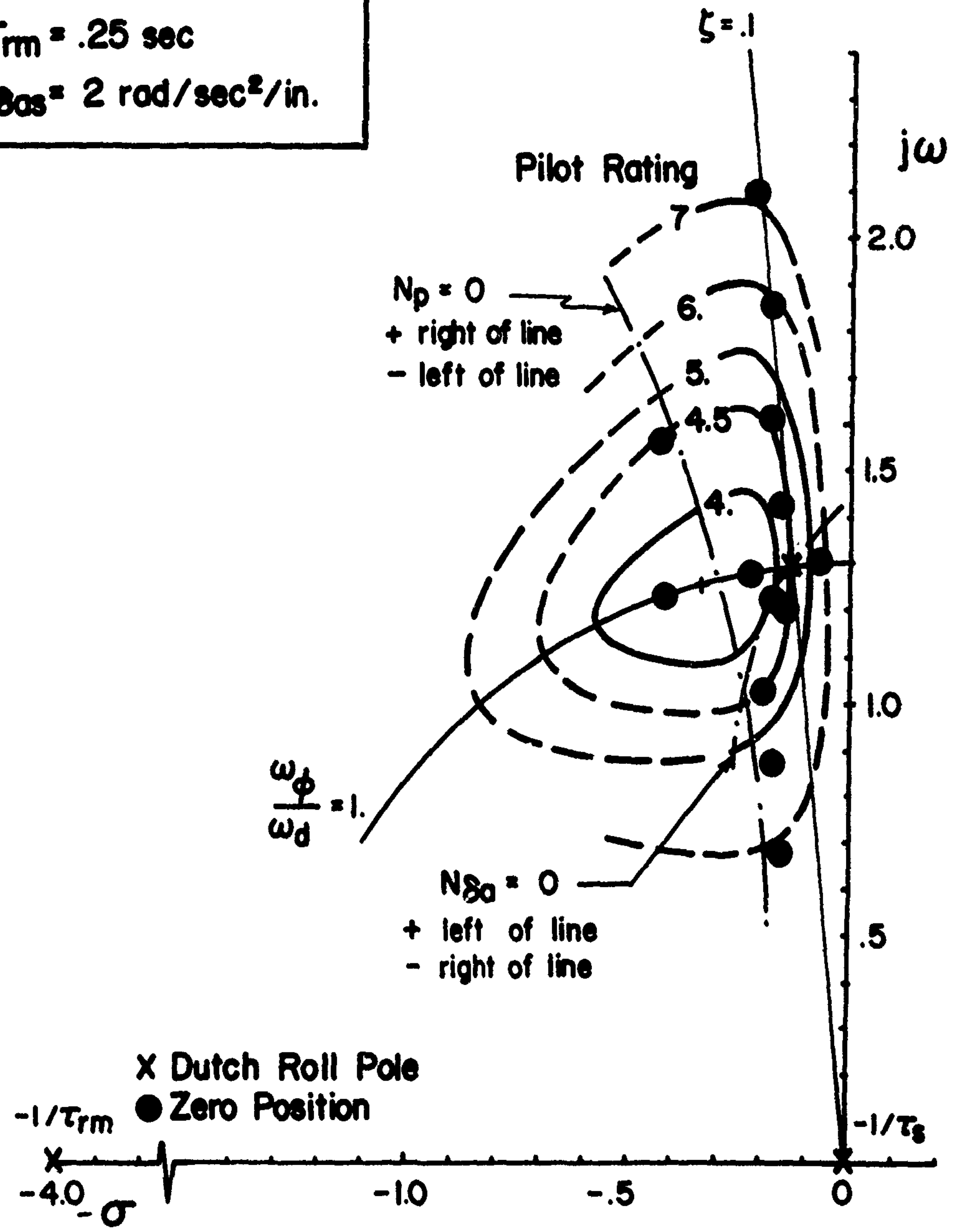


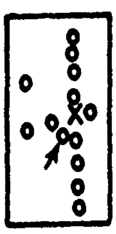
FIGURE IV-3 PILOT RATING CONTOURS AS A FUNCTION OF ROLL TRANSFER FUNCTION ZERO POSITION. ω_d = 1.3 RAD/SEC the high-frequency machine this placed the φ/δ_a transfer function zeros generally below and to the left of the pole, a position calling for essentially zero aileron yaw and slightly positive yaw due to roll rate (note lines of $N_{\delta a} = 0$ and $N_p = 0$ superimposed on the rating contours); the exact value is apparently not critical, however, and reasonable variations about the optimum result in virtually no change in flying qualities.

For the low-frequency airplane, however, the best position for the transfer function zeros is almost directly to the left of the pole, generally along the $\omega_\varphi/\omega_d = 1$ line. This corresponds to fairly large positive aileron yaw (sometimes termed "proverse yaw") and zero or slightly negative yaw due to roll rate, N_p. Variations in sign and magnitude of the latter are apparently not critical, but the need for positive $N_{\delta a}$ is clear.

Thus, in addition to the effects of large variations in $N_{\delta a}$ and N_p, one is led to look for fundamental differences in handling associated with ω_d, and for reasons why positive aileron yaw should help to optimize the low frequency but not the high frequency airplane.

<u>Base Configurations - $N_{\delta a} = 0$, Low Dutch roll Excitation</u>

<u>High frequency airplane.</u> The base configuration for $\omega_d = 2.3$ rad/sec was H-96-14 (see sketch for relative position of φ/δ_a poles and zeros) which was flown extensively in the program of Reference 1 as Configuration 11. Here again the consensus was that it was a "3.0" airplane, downgraded slightly because of its turbulence response. This is also close to being the "optimum" high frequency airplane tested.



A time history of 30 seconds of the mid-portion of an approach with this airplane is shown as Figure IV-4; generally small control inputs, good localizer performance, and moderate yaw rate, roll rate, and sideslip excursions are evident.

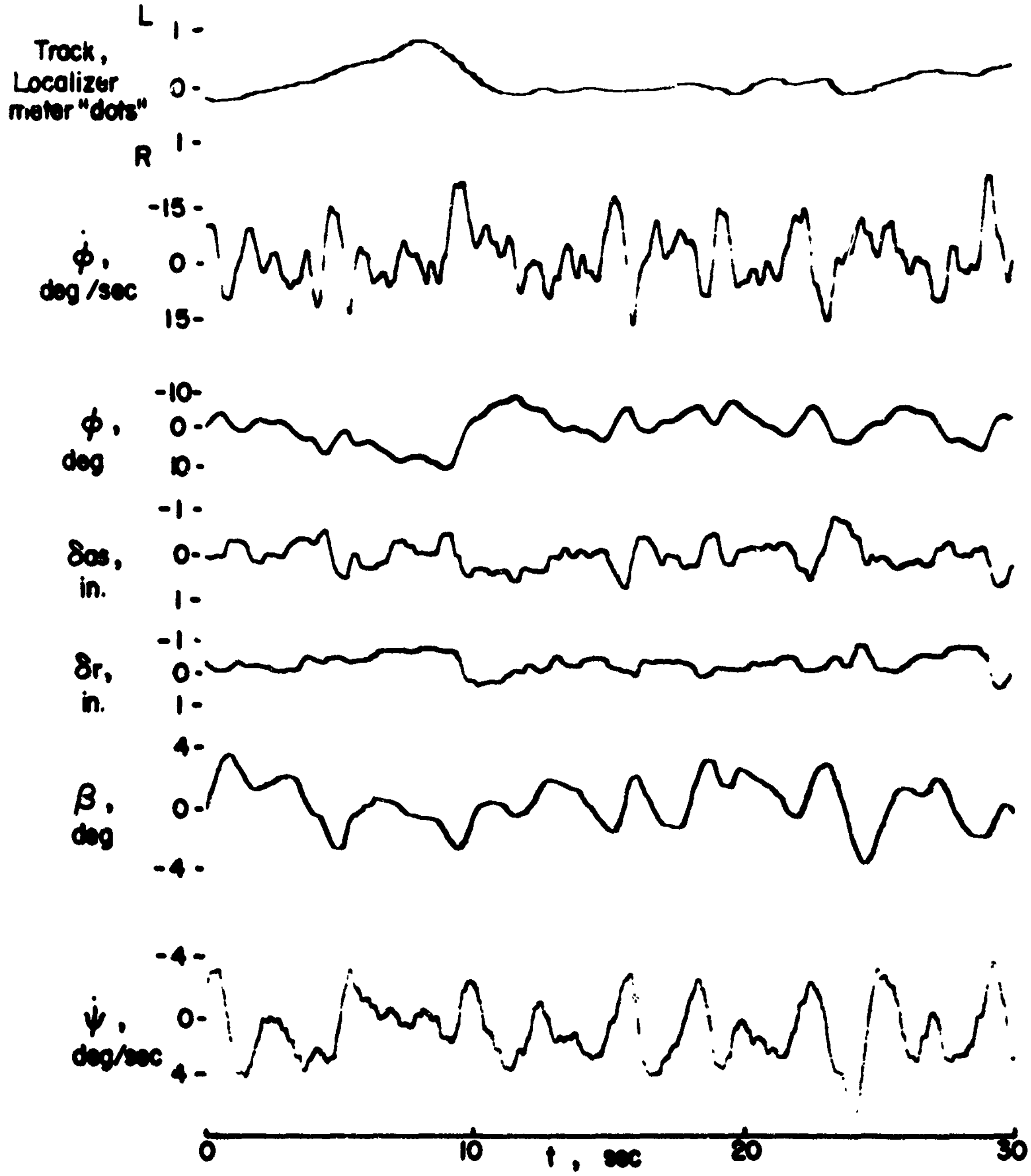
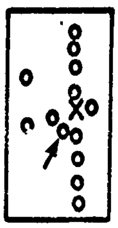
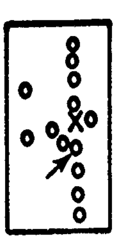


FIGURE IV-4 HIGH DUTCH ROLL FREQUENCY BASE CONFIGURATION, H-96-14

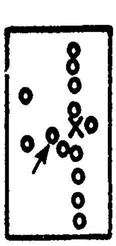


Low frequency airplane. The base configuration $\omega_d = 1.3$ rad/sec airplane was designated L-95-15 (see sketch), and was flown in the Reference 1 program as Configuration 9. Again it was rated 4, mainly due to sloppiness in yaw, with a tendency for sideslips to develop. A portion of an approach time history for this airplane, Figure IV-5, shows larger stick motions, localizer deviations, and airplane motions than those for the high frequency machine of the previous figure; although the sideslip excursions are large, they are not sustained, and the rudder activity is about the same as for the $\omega_d = 2.3$ rad/sec machine, indicating that the positive N_p (=.13) is doing a sufficiently good job of keeping the ball (of the turn-and-bank indicator) from going in the wrong direction that the pilot is not having any problem controlling his average heading sufficiently well with aileron.

The Effects of Small Departures from the Base Configurations



High frequency airplane. Departing from the near-optimum base configuration with a combination of small negative $N_{\delta a}$ and positive N_p, but still little Dutch roll excitation (Configuration H-93-11), yields a still satisfactory airplane. The adverse yaw was usually detected, but it caused no problems during the approach. The turbulence kept the pilots "busy" enough to prevent them from rating it better than 3.0.



Moving to the other side of the base configuration with positive aileron yaw and negative yaw due to roll rate (H-98-20) produced essentially the same results. The Dutch roll did not interfere with the task and the airplane could be flown with very little coordination of the rudder, which was appreciated. Again the level of turbulence kept the pilots from rating it better than 3.0. The flight records consistently shows small control inputs including very little rudder pedal activity, good localizer and glide slope performance, and moderate airplane motions.

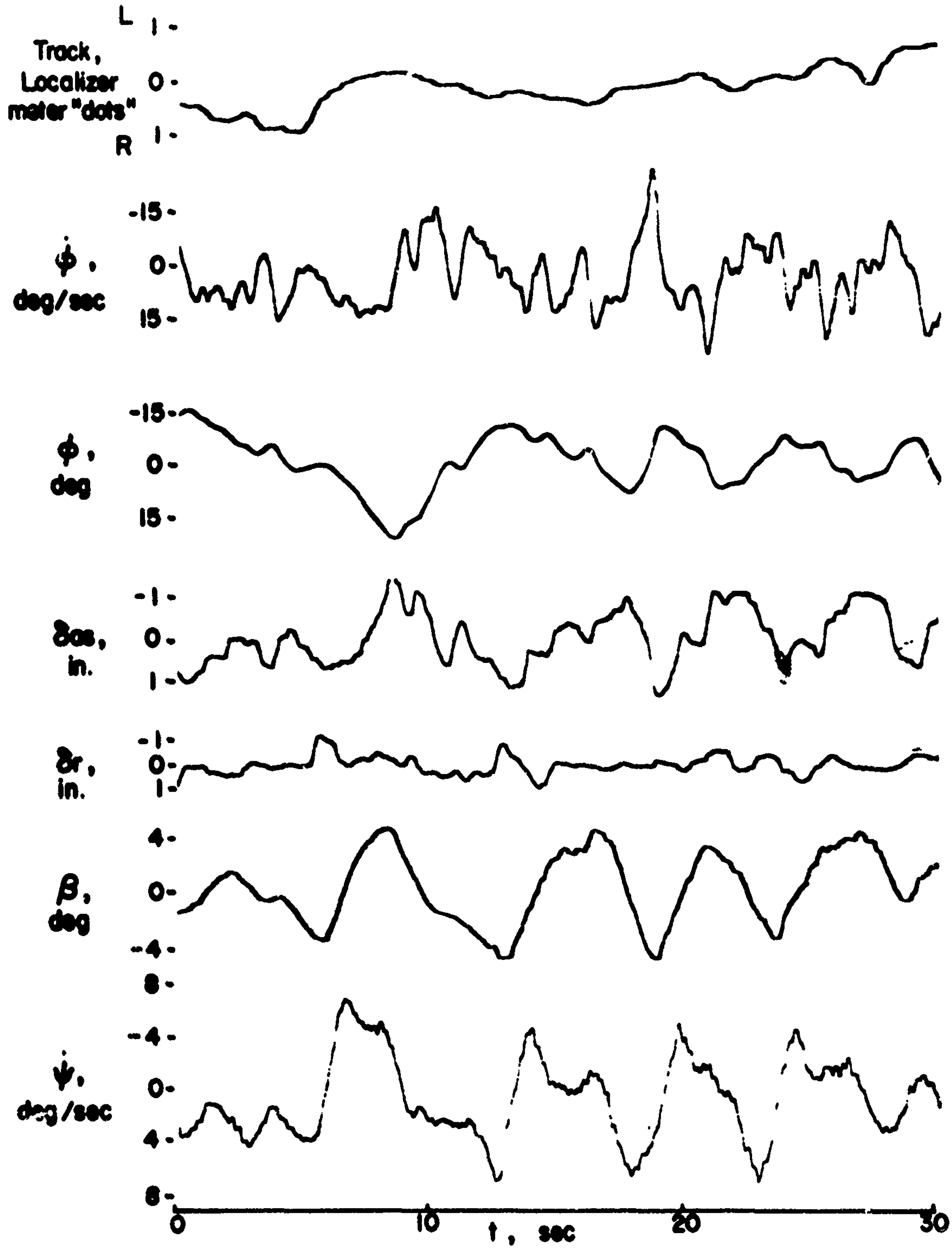
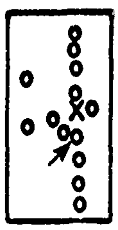


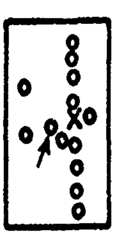
FIGURE IV-5 LOW DUTCH ROLL FREQUENCY BASE CONFIGURATION, L-95-15

To sum up, the flying qualities remain uniformly good for reasonable variations in $N_{\delta a}$ and N_p about zero for the high directional stability case. The flying can be done with the stick alone, if desired.

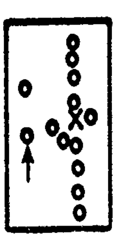


Low frequency airplane. Proceeding in a similar way to Configuration L-93-13 by adding negative aileron yaw and slightly more positive N_p to the base configuration, one again sees little change in flying qualities as far as numerical rating goes, but the commentary begins to pinpoint the nature of the problem with these low frequency airplanes: "Low directional stability makes it necessary to worry about the rudder and sideslip all the time. Needs sideslip control to give me the heading that I want. Otherwise nothing wrong with the roll or Dutch roll excitation that I can see. Not an awful lot of Dutch roll in evidence, just sloppy in heading." "In still air it was quite adequate... but [in turbulence] on the approach there was a continual problem with large sideslips. Coordination was difficult in a low frequency sense and occasionally the sideslips became so large that the control forces required were objectionable."

The control forces mentioned here were roll control forces, not rudder forces, and were associated with aileron inputs required to counter the sideslip-induced rolling (L_β = -16). Rudder response was very good for this low directional stability airplane; for some pilots the nominal setting of $N_{\delta rp} \doteq$ -.3 rad/sec^2/in was too sensitive for effective use, in which case it would be lowered by the safety pilot to a satisfactory level - that is, until the evaluation pilot stopped making that particular comment.



Going now to Configuration L-100-18, which has slightly positive aileron yaw and yaw due to roll rate, but in a combination which still gives about the same level of Dutch roll excitation as the base ($N_{\delta a}$ = 0) airplane, we find on the average a slight improvement in rating. The problem with sideslip has not gone away as indicated by the comment, "Didn't see much in Dutch roll excitation. I did realize at the end of the run that the reason I was having so much trouble with localizer...was that the ball was getting out and I wasn't aware of it...I'm not really on the [average] heading that I think I'm on," but apparently this can or perhaps should be handled with stick alone: "...coordination is not required...In general the performance was quite good for a minimum pilot workload...I can watch the ball for aileron inputs...although I have the feeling I would like to [move stick and rudder in the same direction], the consequences of coordinating are too much roll rate. Therefore my preference is to stay off the rudder." And he did, as indicated by the portion of approach time history shown in Figure IV-6. Comparing this with the approach of Figure IV-5, the base configuration, generally similar levels of activity (except rudder) and performance are evident.



This indication of some improvement in flying qualities due to the presence of positive $N_{\delta a}$ may be pursued further by examining Configuration L-100-33, which, like the previous one has $\omega_{\varphi}/\omega_d = 1$, but an even higher level of $+N_{\delta a}$ (1.75 vs 0.75 rad/sec^2/in). The yaw due to roll rate, however, is negative, making the configuration analagous to the high frequency case just discussed, H-98-20.

It should be noted that with this combination of $N_{\delta a}(+)$ and $N_p(-)$ the response to a roll control input will show an initial yaw acceleration in the direction of roll, to be countered slightly later by one in the opposite direction as the roll rate builds up. This is significant in the piloting problem, as evidenced by the following very perceptive comment: "Dutch roll excitation was small. It didn't interfere appreciably with performing the ILS task. I did find the need for rudder. However, I found it to be natural as it was in the same direction as the aileron input. I did notice that when I put in rudder initially in the same direction as roll that I tended to overcontrol, then as the rate built up I seemed to have the proper amount of rudder in to keep the turn coordinated. ...I was exciting the Dutch roll with my own [initial rudder] inputs. However, the total overall coordination was good. The ILS performance was good, pilot workload was certainly minimal. The fact...that I do tend to overcoordinate a little makes it totally mildly unpleasant."

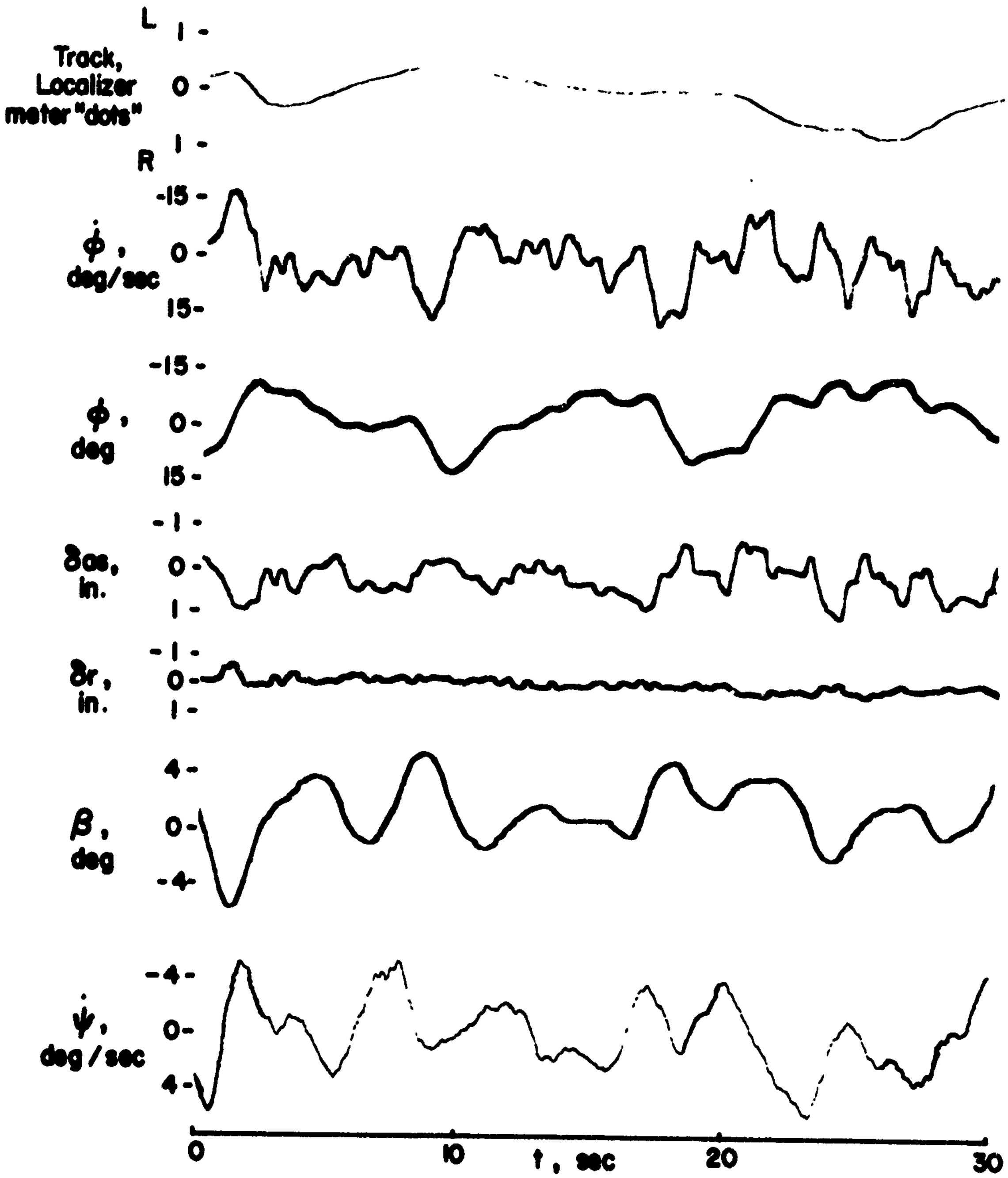


FIGURE IV-6 EFFECTS OF SMALL $+N_{\delta a}$ ON THE $\omega_d = 1.3$ RAD/SEC AIRPLANE

That particular run, and several others, were rated 3.0. On a few passes the now-familiar sideslip problem entered the picture and caused a downgrading to a 4.0 rating, but all in all there was noticeable improvement over the base configuration.

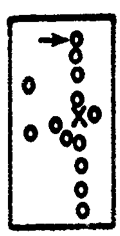
In summary, this feature of the "optimum" low frequency airplane requiring a healthy portion of positive aileron yaw and much less positive N_p than the "low Dutch roll excitation" airplane may stem in large part from the fact that it allows the pilot to coordinate naturally - that is, move stick and rudder in the same direction - without penalty. The base configuration and the other two close to the Dutch roll pole don't require much coordination, but if the pilot can't resist moving his feet with his hands he will himself be causing a good deal of Dutch roll excitation; on the other hand, they can't be flown without rudder, either, because of the sideslip excursions resulting from turbulence, if nothing else. Relatively independent use of the two controls is called for, something which is not always easy to do, especially on instruments. The "optimum" low frequency airplane doesn't demand this independent control use.

The high frequency, good directional stability airplanes discussed previously can be flown successfully without rudder, so the above argument doesn't apply, and in fact the effect isn't observed.

Observations, based on analytical studies, that low directional stability airplanes would benefit from the addition of positive aileron yaw have been made in the past by Pinsker (Reference 15). However, the directional stability here is probably much larger than the levels he envisioned, and the piloting situation is much more complex than the bank angle control with aileron which he was treating. The thrust of his argument was that $N_{\delta a}$ would effectively increase the closed loop natural frequency; that is not the point of the preceding discussion.

Actually providing positive aileron yaw is not difficult, requiring simply a mechanical interconnect between aileron and rudder (in fact, this is done on many light planes now, but for the purpose of meeting FAR 23.177 of Reference 16, a requirement that it should be possible to unbank the airplane with rudder alone, not for the reasons under discussion here).

The Effects of Large Positive Aileron Yaw



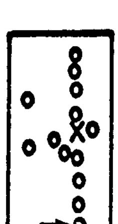
Although the preceding discussion has dwelt upon possible benefits of positive aileron yaw, it certainly can be overdone, as Figures IV-3 and IV-4 indicate. The highest levels tested, $N_{\delta a} = 5.25$ rad/sec^2/in for the low frequency case (L-162-11) and 8.75 rad/sec^2/in for the high frequency airplane (H-142-06), resulted in average pilot ratings of 7.0.

The commentary ran as follows: "Extreme amount of proverse yaw on that one...on the glideslope there was excitation of the Dutch roll. It was really upsetting me at times." "That configuration was quite difficult to fly. Large sideslip excursions resulted from both control inputs and turbulence. There were excessive rolling motions due to sideslip...making glideslope and localizer control quite difficult."

Coordination was difficult, as indicated by, "I find the rudder coordination is unnatural... I tend to augment the Dutch roll..." and, "The initial response was such as to require cross-controlling. [This was] difficult, if not impossible, for me to figure out how to do..."

Portions of two approaches, one with the $\omega_d = 2.3$ rad/sec and the other with the $\omega_d = 1.3$ rad/sec airplane are shown in Figure IV-7. Extreme yaw rate accompanying high levels of stick activity may be noted.

The Effects of Large Negative Aileron Yaw



The largest levels of negative $N_{\delta a}$ tested produced average ratings of 6.0 for the low frequency case ($N_{\delta a} = -1.25$) and a little less than 4.5 for the high frequency airplane ($N_{\delta a} = -3.25$). Here coordination is at least "natural" - stick and rudder move in the same direction - and most pilots find this characteristic easier to cope with than large positive $N_{\delta a}$.

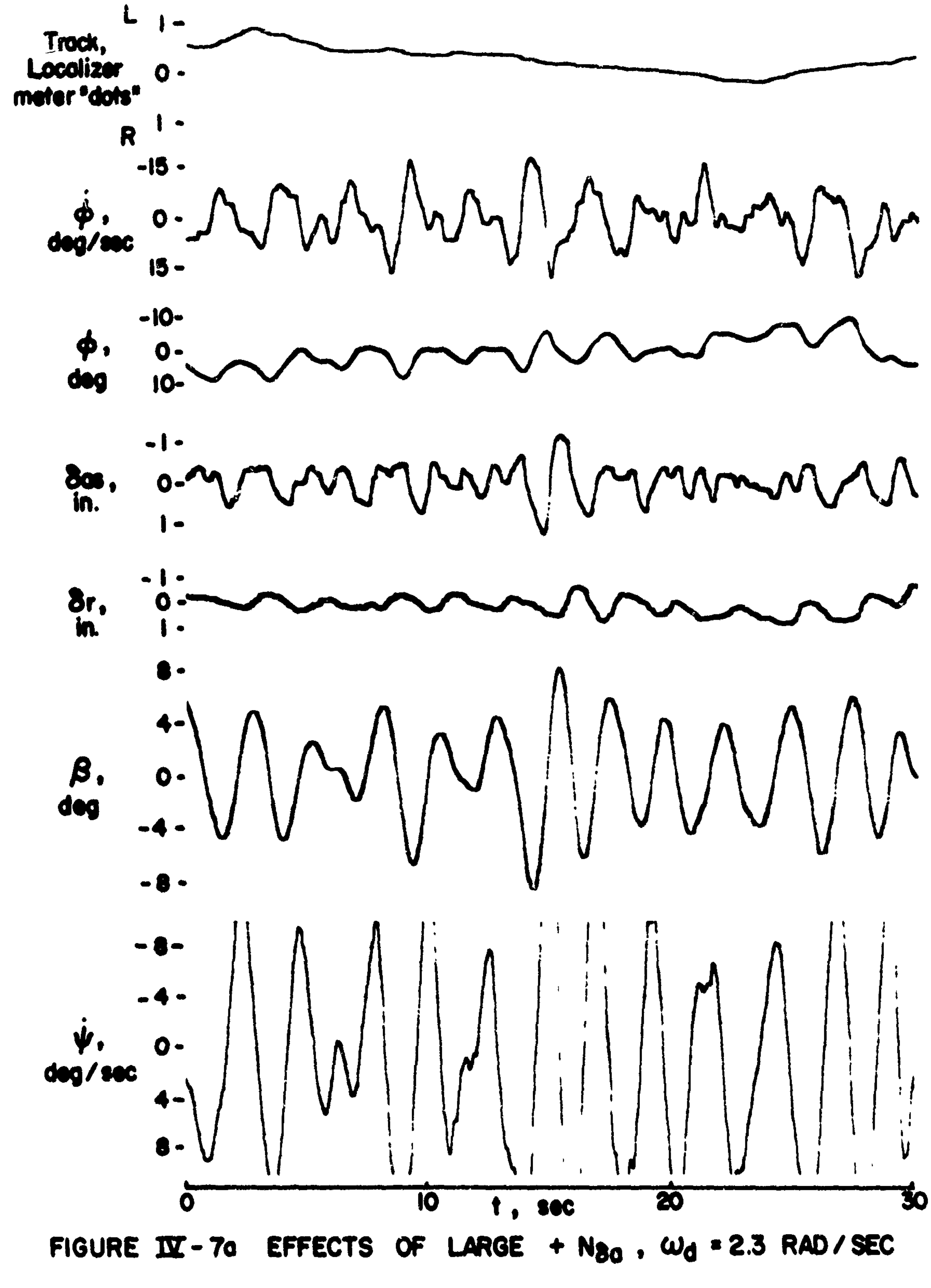


FIGURE IV-7a EFFECTS OF LARGE + $N_{\delta a}$, ω_d = 2.3 RAD/SEC

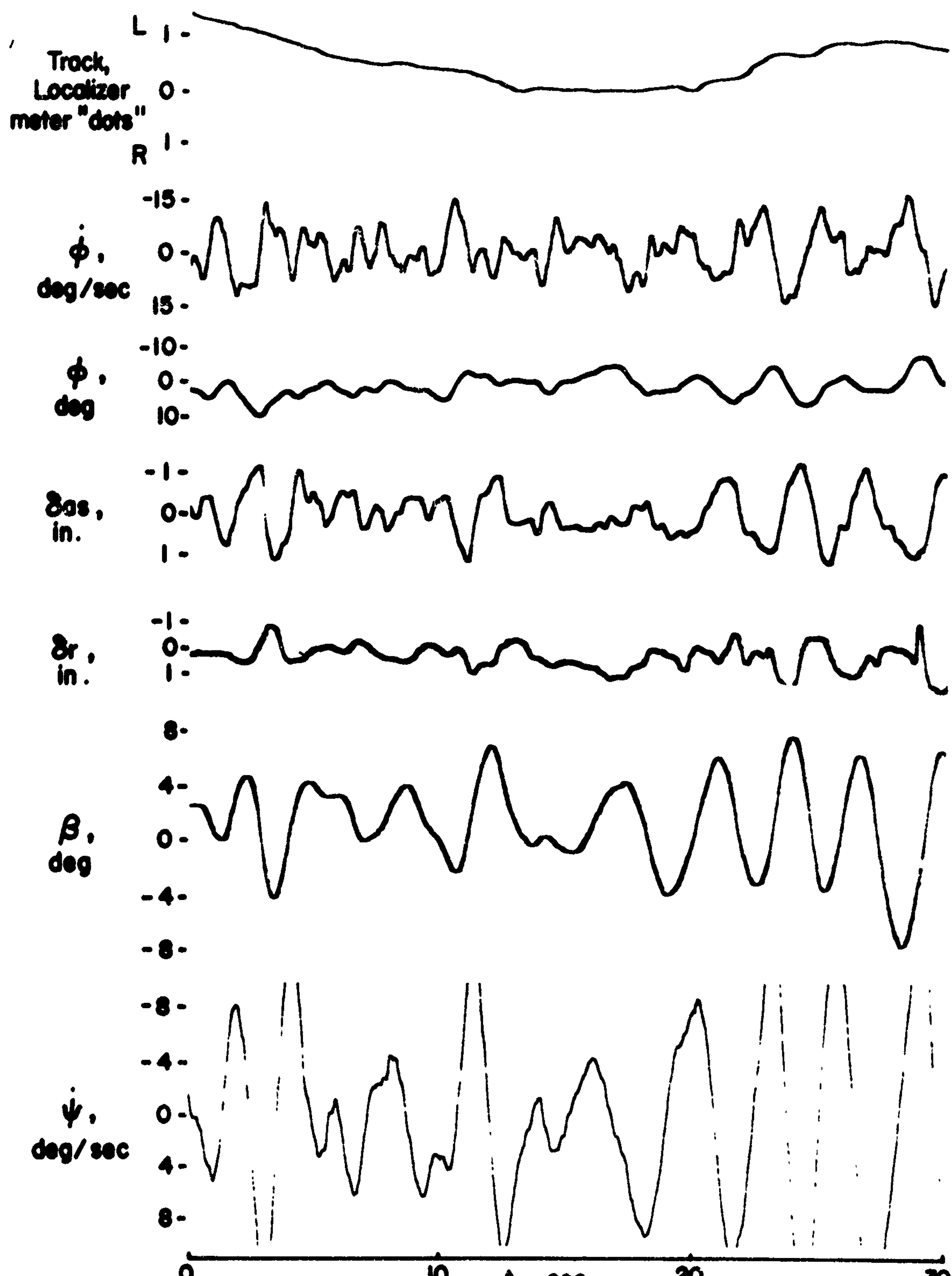


FIGURE IV- 7b EFFECTS OF LARGE $+N_{\delta a}$, ω_d = 1.3 RAD/SEC

The following comment covers about all that is important with the high frequency airplane (H-72-15): "Dutch roll excitation on the last run was small. I was surprised because in [smooth air maneuvering] there seemed to be [considerable] adverse yaw...without coordination it was limited in control power and required a fair amount of rudder to get the airplane to turn. I found that coordination was in the proper direction and fairly easy to do. I was better at coordinating than I thought I was going to be...on the glide slope it didn't seem to bother me very much."

The apparent loss in roll control power is of course due to the large dihedral present ($L_\beta = -16$).

The low frequency airplane (L-54-24) does not fare so well, however, with the problem of large sideslip excursions again entering the picture. The commentary runs, "Dutch roll excitation seems to be quite large with large steady state sideslips which I find quite uncomfortable and often [the airplane] is going in the wrong direction. I want to be turning left and the sideslip is making me go to the right... I had a fair amount of difficulty with heading control all along. The rudder coordination seems to be in the right direction; however, it seems to be giving me a tough time and is taking a lot of my attention away from flying the approach."

Differences Between Pilots

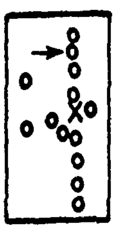
The results presented in Figures IV-2 and IV-3 are the averaged ratings of four pilots, and care has been taken in the discussion thus far to present commentary which applies to that average rating level. As the program progressed, however, it became apparent that there were systematic differences between these evaluation pilots, either in technique or in outlook, which resulted in wide variations in ratings for certain configurations.

Before discussing these variations, it must be emphasized that the four were active, experienced test pilots, and their ability to fly the task and use the rating system was beyond reproach. The fact that clear differences can exist in such a group is itself important, and an examination of these differences is helpful in interpreting the overall results.

Figure IV-8 presents the results which were faired to construct the $\zeta_\varphi \omega_\varphi$ = .20-.22 curve of Figure IV-1a and the $\zeta_\varphi \omega_\varphi$ = .15-.21 curve of Figure IV-1b. These ratings for individual pilots are themselves averages, but they tended to be self consistent, generally within one or one and one-half units for a given configuration.

It is clear that Pilot A is not much bothered by levels of $\omega_\varphi / \omega_d$ which Pilot B considers nearly disastrous; Pilot C agrees with B on the high frequency airplane, but in the low frequency case he sides with D who is not far from the final average curve.

In examining the reasons for these differences the factor of experience certainly must be accounted for: Pilot A had far more practice than the others flying the simulator and the approach; Pilot D had the least. Pilot A had the most experience with light airplanes; Pilot D had the least. All had military training backgrounds, although Pilot A had predominantly propeller-driven airplane experience, while the others had jet fighter experience. All except Pilot A were helicopter pilots.



Configuration L-143-10 provides a good example of an airplane over which there was considerable disagreement. Pilot A comments, "... low frequency, a lot of proverse yaw. A lot of Dutch roll excitation [while feeling it out], and again it surprised me - there wasn't any on the glide slope. Just the sideslip again and I wasn't really aware of the proverse yaw. Call it a 4.5 due to the upsets in yaw."

Pilot B finds the airplane "clearly unacceptable. Large Dutch roll excitation, very large sideslips... The fact that you come out somewhere near the glideslope is as much luck as it is anything else. I think that we're really

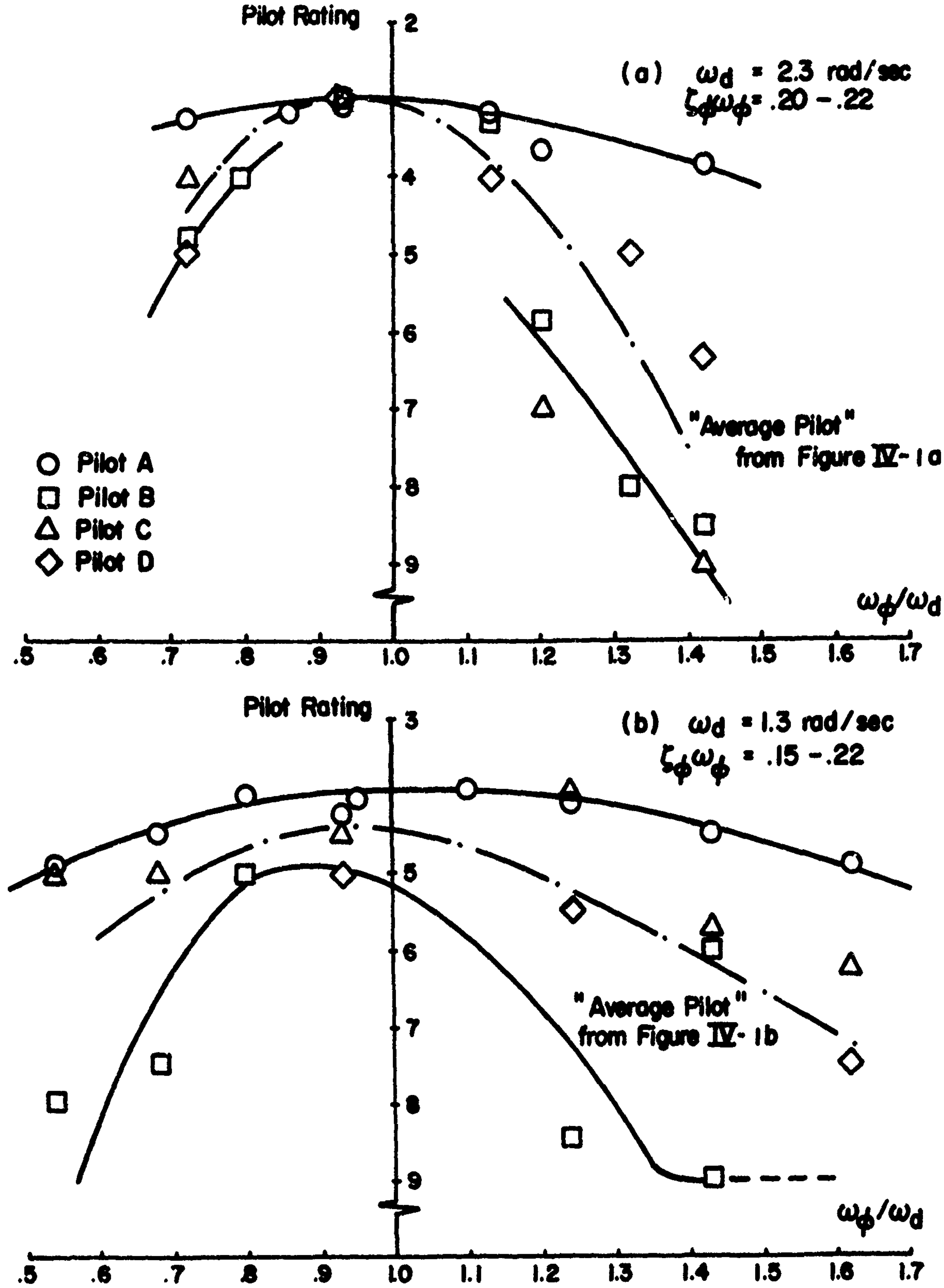


FIGURE IV-8 PILOT RATING AS A FUNCTION OF ω_ϕ/ω_d. INDIVIDUAL PILOT AVERAGES.

approaching the limit of controllability... it requires intense pilot compensation which certainly can be done, [but] the airplane has major d ficiencies..." He rated that pass 9.0.

Pilot C noted, "... excitation of Dutch roll with controls, proverse yaw from δ_a - not as bad on approach as I thought it would be. Had some trouble with coordination on approach, [but] could ride out most disturbances." The rating was 5 to 6.

Pilot D complained mainly of not being able to hold a desired bank angle and excessive roll-yaw coupling, and rated the airplane 6.0.

Figure IV-9 features portions of the approaches commented upon above. Pilot A is clearly having a good approach, putting in generally small stick and rudder deflections, knocking down the occasional larger-than-usual yaw excursion with rudder; Pilot B, on the other hand, is working much harder, the airplane motions can only be described as wild, and the approach at that point is not going well; the traces for Pilots C and D show intermediate levels of activity and airplane motion and satisfactory localizer performance. The four are, so to speak, calling them as they see them.

This configuration was not an isolated example. The flight records tend to support the divergence of opinion wherever it occurs, whether at high or low $\omega_\varphi / \omega_d$, high frequency or low frequency. One is led to the conclusion that some pilots, like Pilot A, can work on the yaw problems with the rudder almost independently of what is happening in the roll department. Others, like Pilot B, find it difficult to uncouple their hands and feet; with the high $\omega_\varphi / \omega_d$ configurations this greatly accentuates the Dutch roll excitation, and the more vigorous the attempts at control, the more extreme the airplane motions become.

<u>The effects of exposure and training.</u> A configuration would normally be rated after one or two approaches, and would be reflown at least once to check the repeatability of the rating. As the divergence in rating between

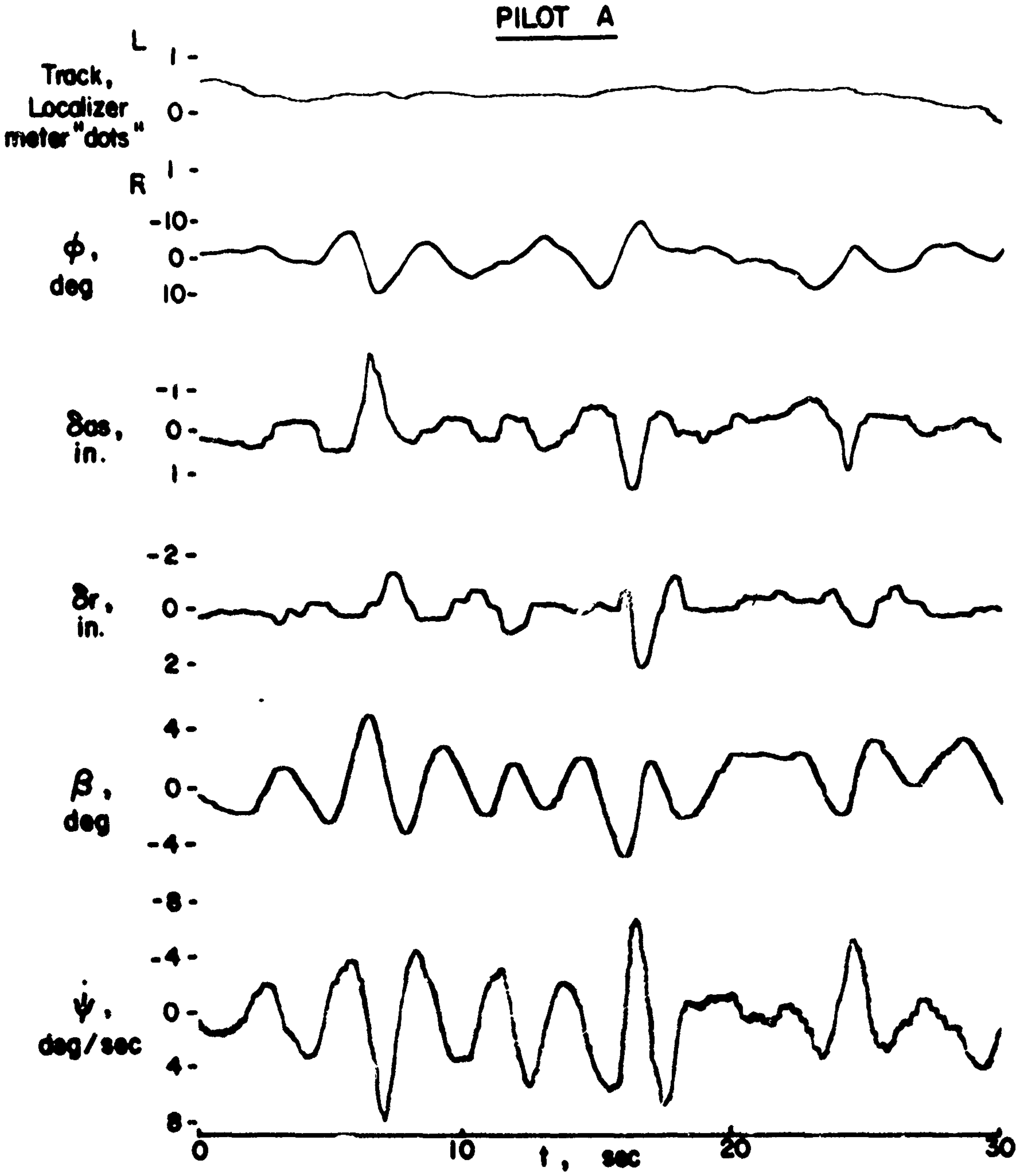


FIGURE IV- 9 DIFFERENCES BETWEEN PILOTS, CONFIGURATION L-143-10

PILOT B

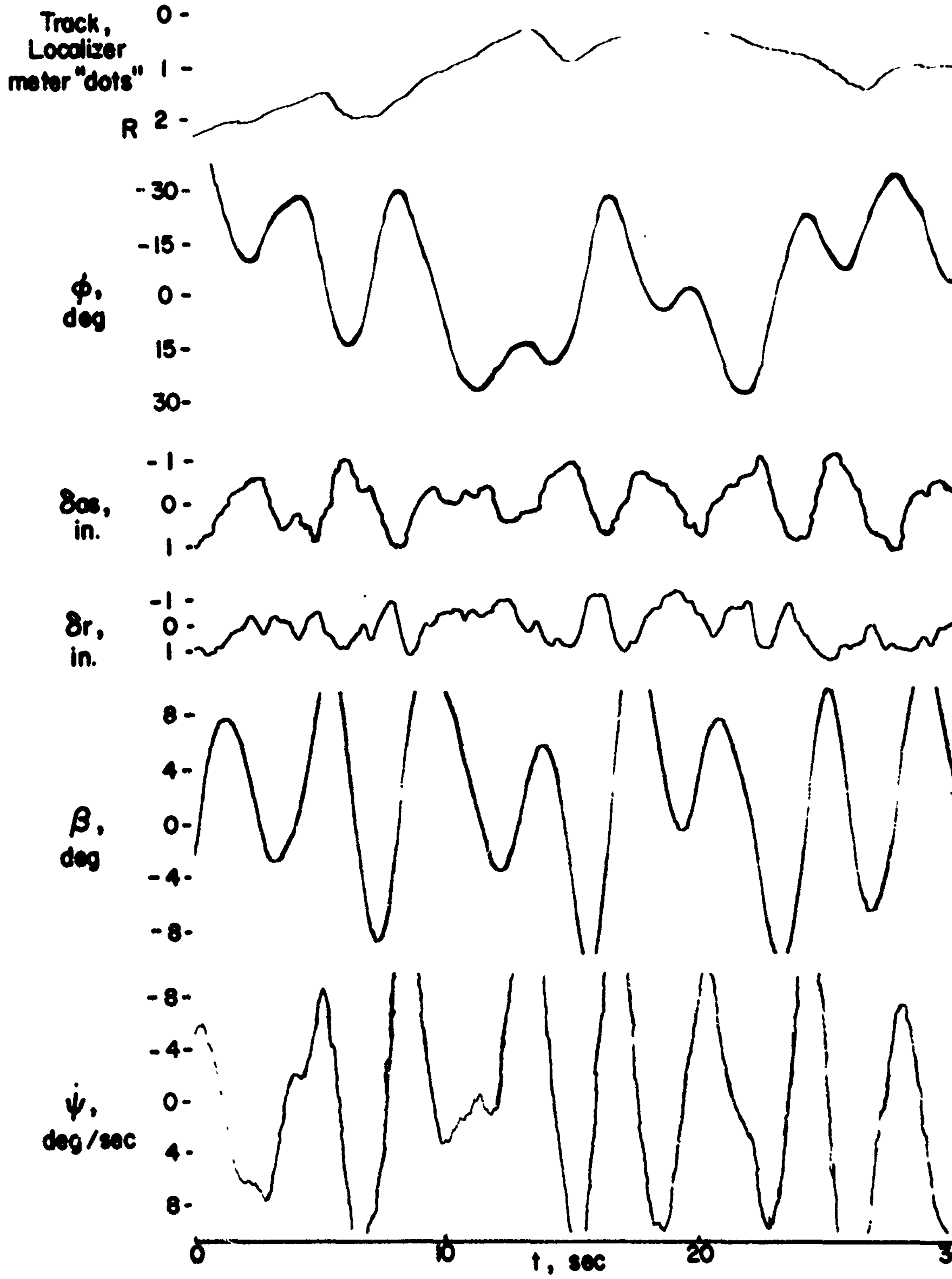


FIGURE IV-9 Continued

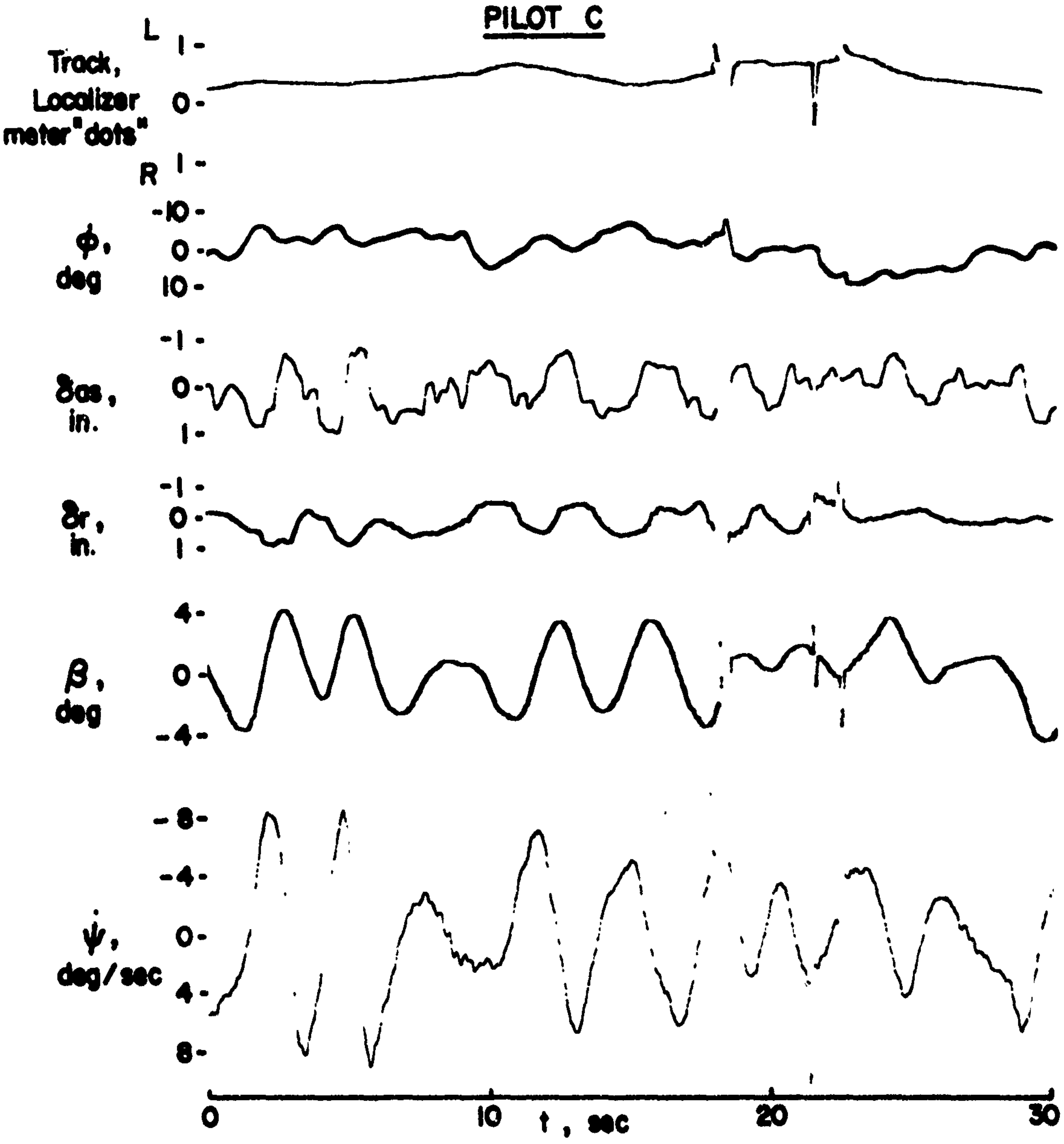


FIGURE IV-9 Continued

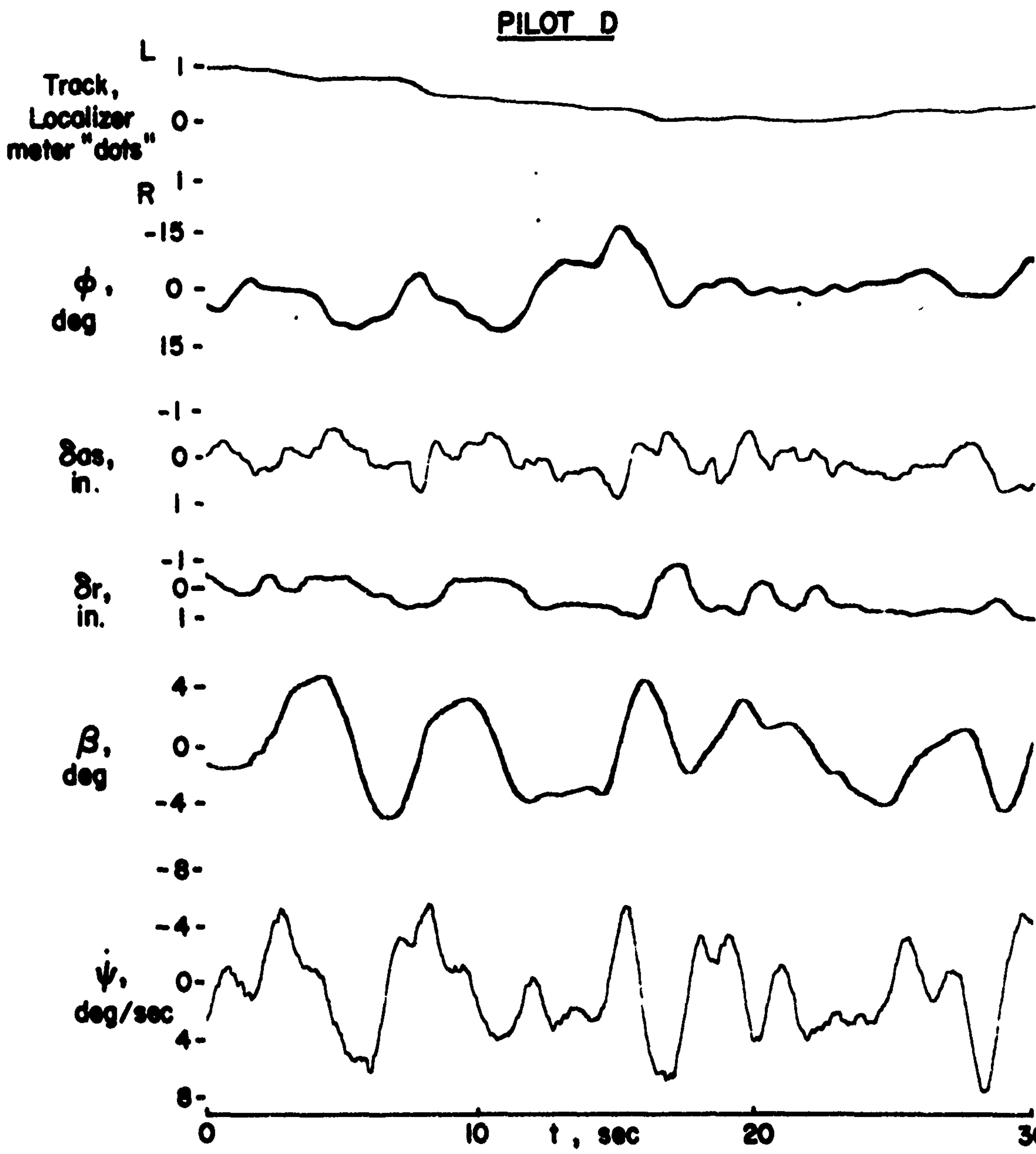
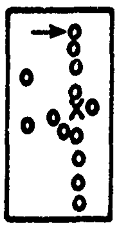


FIGURE IV- 9 Concluded

pilots began developing, it became important to know whether or not the very poor ratings would change if the pilot were allowed to fly the same airplane several times in succession in order to gain familiarity with a difficult characteristic or to evolve a more effective technique.



The results of such an exercise with Configuration L-162-11, the low frequency airplane with the highest level of positive aileron yaw, are typical. Pilot C rated the first approach 7.5, commenting, "Lot of Dutch roll excited by δ_a. Could stop the oscillation with δ_r only by working hard. Controllable but performance not adequate." A portion of flight record for this run confirms that there was considerable control activity and airplane motion. This is shown in Figure IV-10a.

At this point he was encouraged to fly as many passes as he wanted with that configuration and to experiment with different control techniques. The second approach (Figure IV-10b) was rated 6.0, and reflected some exploration of rudder versus aileron use: "...δ_r excites Dutch roll. Eventually gave up on rudder and used only aileron. Performance adequate compared to the previous run, but had to work very hard." The point at which he stopped using rudder vigorously is apparent in the figure - the yaw rate trace does start to calm down somewhat.

The third trial was also rated 6.0, with the comment, "[I] tried a little different technique, controlling heading with rudder. Not very successful. Roll excursions from turbulence require lateral control. Large sideslip excursions... Performance adequate but hard work." A portion of the record for that approach (Figure IV-10c) confirms that the aileron activity was a little less frantic than in the preceding run, and the rudder inputs larger. The yaw rate excursions are moderating somewhat.

The fourth approach with that configuration is shown as Figure IV-10d, and it reflects the final evolution in technique: "Using δ_a primarily. Quite successful if I use high frequency [small amplitude inputs] on lateral control. Performance good, but...working too hard to give it better than a 5.5." The

(a) Pilot Rating 7.5

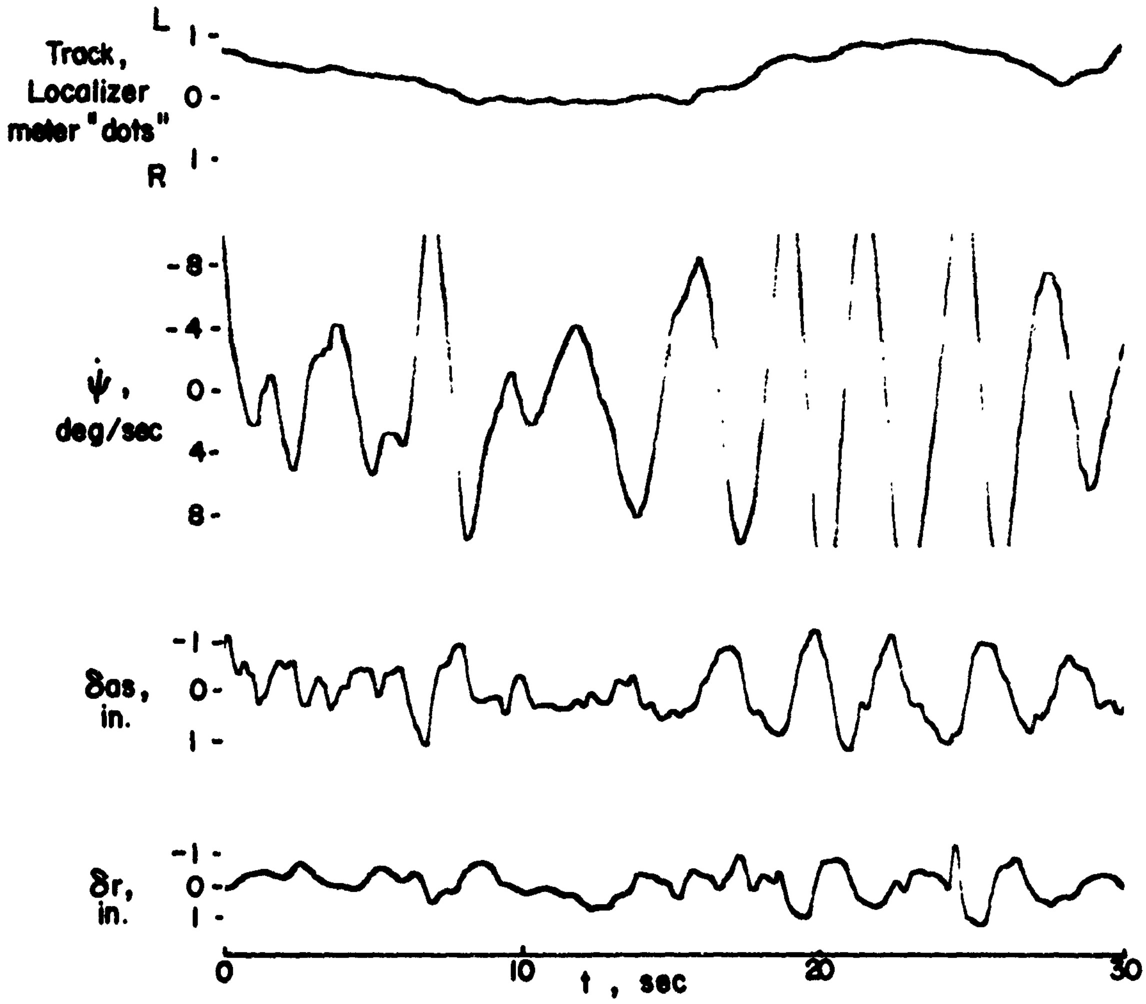


FIGURE IV-10 EFFECTS OF REPEATED TRIALS. PILOT C, CONFIGURATION L-162-11

(b) Pilot Rating 6.0

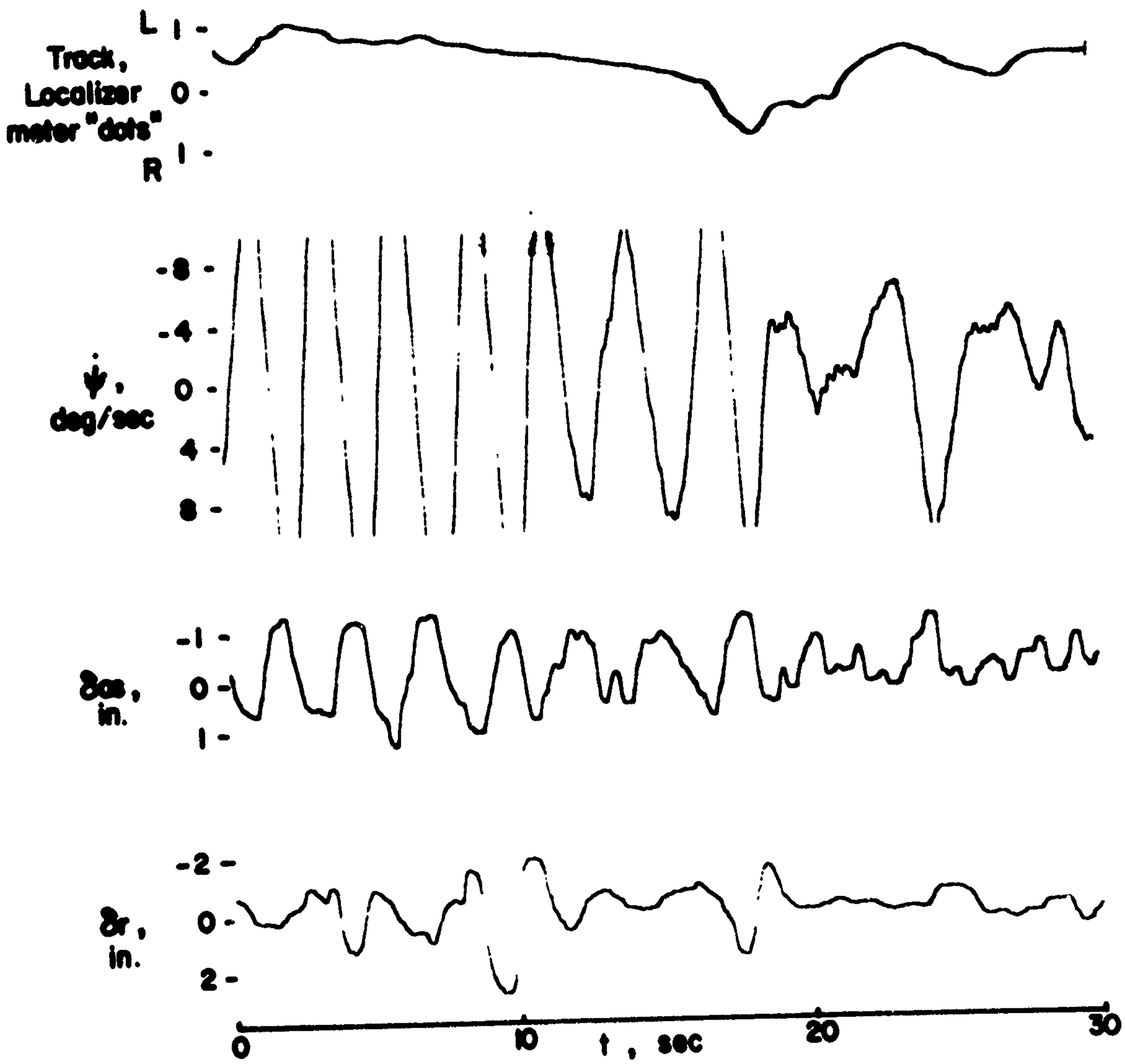


FIGURE IV- 10 Continued

(c) Pilot Rating 6.0

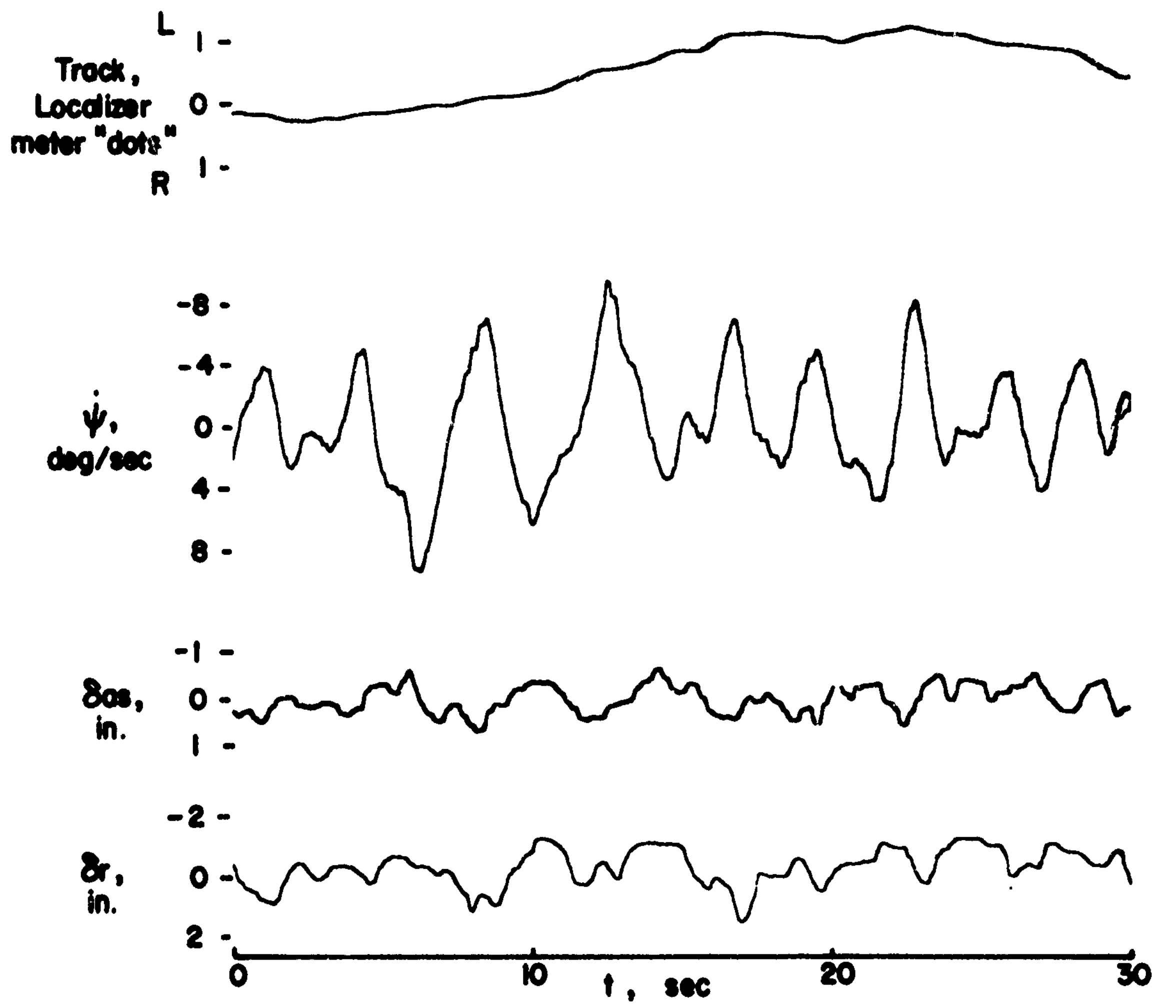


FIGURE IV - 10 Continued

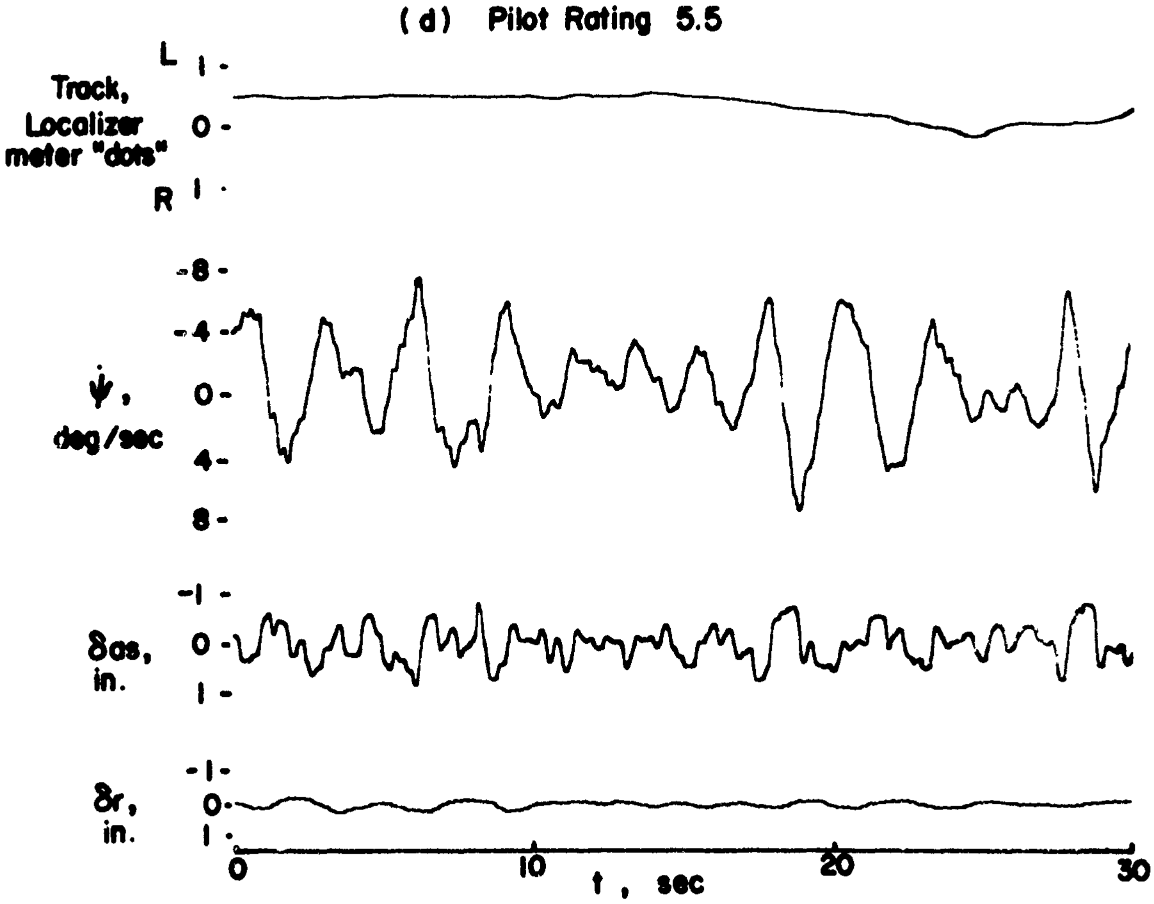


FIGURE IV - 10 Concluded

trace shows virtually no rudder pedal activity and the small, quick aileron inputs mentioned. This was his final rating for the configuration.

A similar exercise with Pilot D resulted in less improvement on the same configuration, from 8.0 to 7.5. He too settled on very small control inputs but felt that the required concentration and workload were still too high to warrant a better rating.

It is clear that practice and either discovery or instruction to the effect that very small control inputs are to be preferred can improve the ratings, but only to a certain point. Pilot A's talent for independent use of aileron and rudder is not easily acquired, and unless really effective rudder action - that is, just enough at just the right time, perhaps in response to angular acceleration or side-acceleration cues - can be effected, large Dutch roll excitation will pose a serious piloting problem.

It was finally decided to fair the data as indicated in Figure IV-1 on the assumption that most pilots are not as talented with their feet as is Pilot A, and that pilots such as B would respond favorably to practice and training.

Comparison With Other Data

As in the roll mode time constant - roll sensitivity investigation of Section III, the most pertinent data for comparison purposes are those of Reference 4. The Dutch roll excitation phase of that program featured configurations having the same dihedral and Dutch roll damping ratio as the present tests, but with a Dutch roll frequency midway between the two tested here, $\omega_d = 1.8$ rad/sec. The roll mode time constant was 0.5 sec, twice that used in the present experiments, and visual approaches were flown.

Figure 16 from Reference 4 is reproduced here as Figure IV-11. The general shape of the rating contours is seen to be the same as those of Figures IV-2 and IV-3; the rating levels are about midway between those for $\omega_d = 2.3$ rad/sec and $\omega_d = 1.3$ rad/sec, but it is difficult to associate

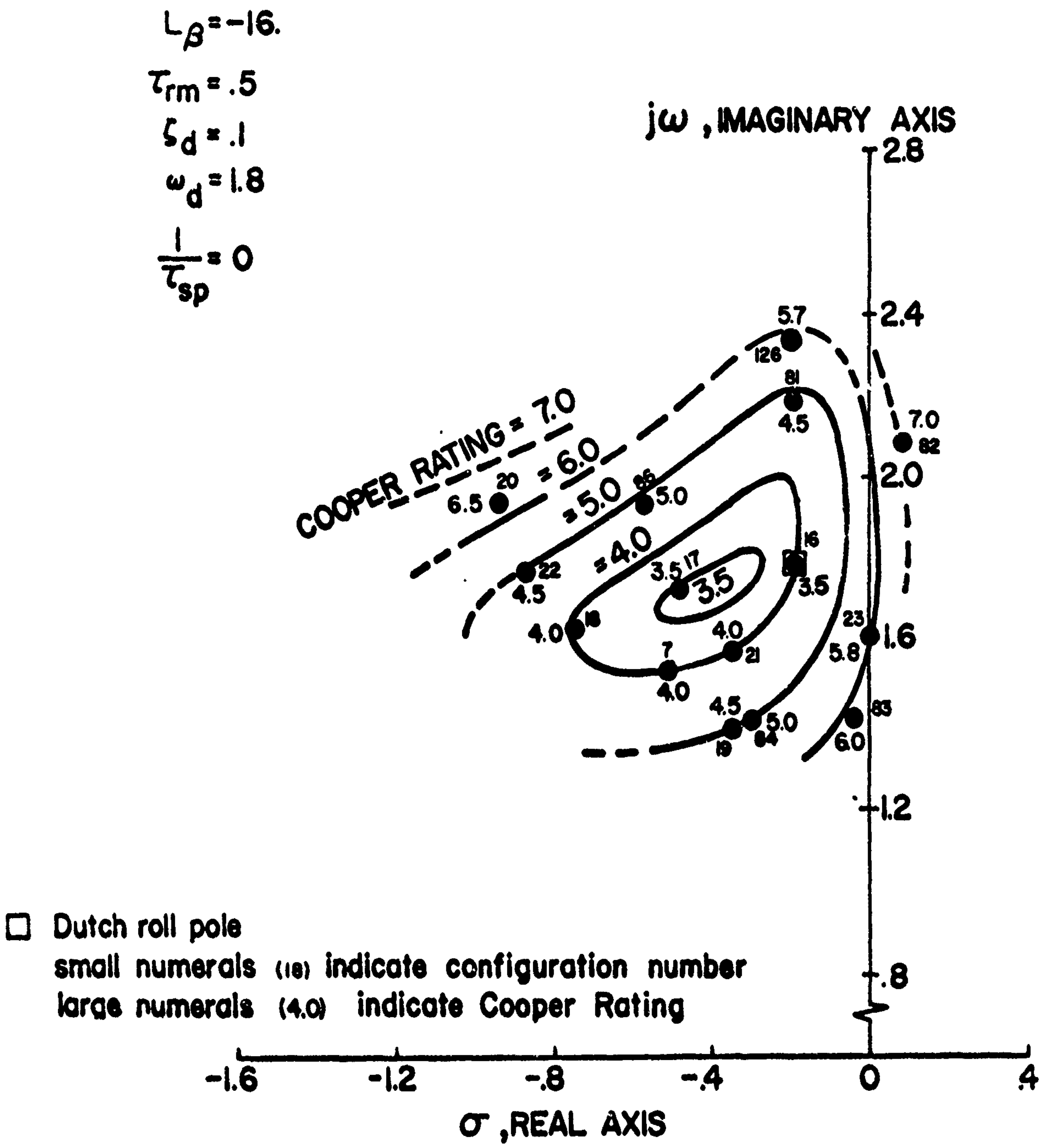


FIGURE IV-11 LATERAL FLYING QUALITIES BOUNDARIES DUTCH ROLL ZERO LOCATION, $\zeta_d = .1$

(FIGURE 16, REFERENCE 4)

that solely with the frequency change because of the lower roll damping present. The difference is only about one-half unit, at any rate.

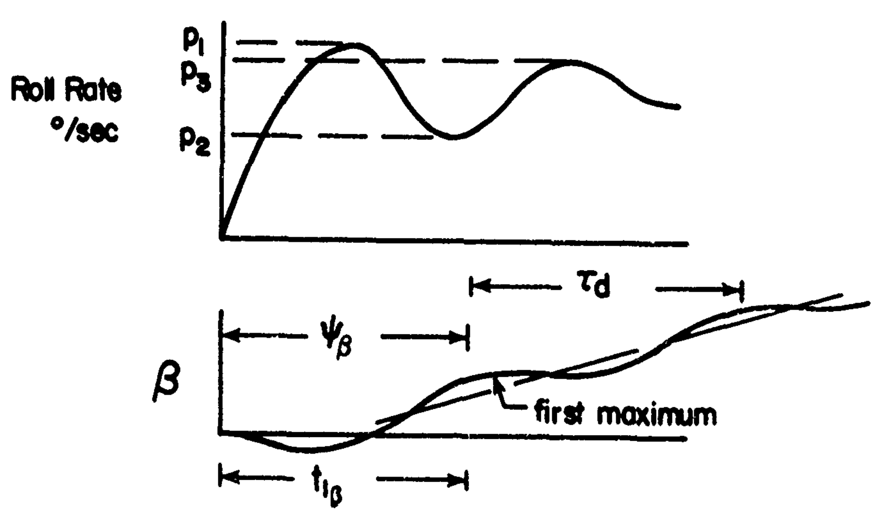
Although $N_{\delta a} = 0$ and $N_p = 0$ lines are not shown, the configuration labeled "7" had those derivative values. Configurations 21 and 16 had small negative $N_{\delta a}$ so the "best" area of the plot is in the positive aileron yaw, slight negative N_p range, generally to the left of the Dutch roll pole with $\omega_\varphi / \omega_d \doteq 1$. Thus these results would seem to have slightly more in common with the present low frequency tests than the high frequency ones, and might be said to add weight to the finding of beneficial effect in positive aileron yaw if the directional stability is low (though $\omega_d = 1.8$ rad/sec is certainly not to be considered too low).

No differences chargeable to the different flight task are apparent.

Comparison With Proposed Military Specification

The specification for flying qualities of piloted military aircraft (Reference 13) includes extensive requirements related to Dutch roll oscillation. These take the form of limitations on roll rate oscillation in terms of the parameters p_{osc}/p_{av} and ψ_β, which are discussed extensively in Reference 8. The background and development of the requirement will not be recapitulated here, but the definitions of the parameters will be reviewed.

Considering the roll rate and sideslip response to a step (right) roll control input (sketch below), the ratio p_{osc}/p_{av} is a measure of the comparative



size of the oscillatory component of roll rate and the average roll rate (rudder pedals free), and is defined as

$$\frac{p_{osc}}{p_{av}} = \frac{p_1 + p_3 - 2p_2}{p_1 + p_3 + 2p_2} \qquad \zeta_d \leq 0.2$$

or

$$\frac{p_{osc}}{p_{av}} = \frac{p_1 - p_2}{p_1 + p_2} \qquad \zeta_d > 0.2$$

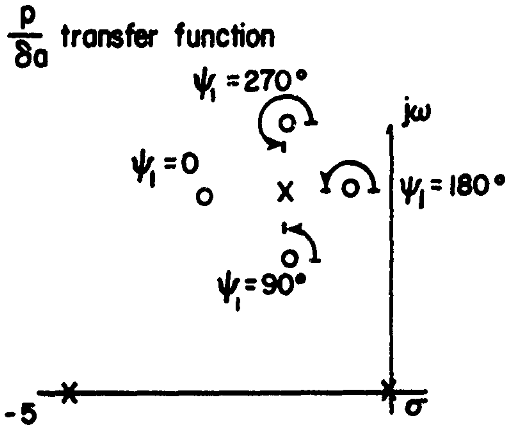
The measure of the lag between the control input and the sideslip response is called ψ_β. In degrees it is given by

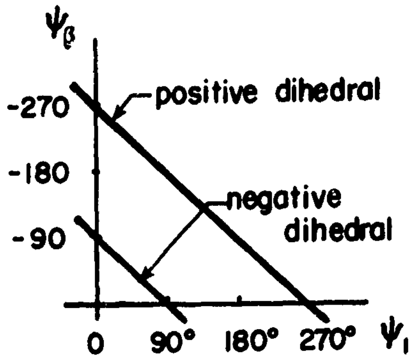
$$\psi_\beta = \frac{-360}{\tau_d} t_{n_\beta} + (n-1)360$$

where τ_d is the damped Dutch roll period and $t_{n\beta}$ is the time required for the oscillation in the sideslip response to reach the n^{th} local maximum for a right aileron input or the n^{th} local minimum for a left command.

The $\frac{p_{osc}}{p_{av}}$ parameter is seen to be akin to the K_d/K_{ss} parameter mentioned previously in the introduction, both being measures of the magnitude of the Dutch roll oscillation.

The importance of the parameter ψ_β lies in the fact that it is uniquely related to the angular position ψ_1 of the zeros of the roll-to-aileron transfer function with respect to the Dutch roll poles sketched on the following page:





Thus it is seen that $\frac{p_{osc}}{p_{av}}$ and ψ_β are an alternative to the $\frac{K_d}{K_{ss}}$, $\frac{\omega_\varphi}{\omega_d}$, ζ_φ method of specifying the various configurations of this report.

The requirement itself is in terms of allowable $\frac{p_{osc}}{p_{av}}$ as a function of ψ_β, shown in Figure IV-12. The boundaries designate the Level 1 (Cooper-Harper 3.5) and Level 2 (Cooper-Harper 6.5) requirements for Flight Phase Category C (terminal flight phases).

The configurations of the present tests are plotted on the figure, using a circle symbol for the low frequency airplanes and a square symbol for the ω_d = 2.3 rad/sec airplanes. The numbers inside the circles refer to the configurations as shown in the sketch on the figure. The number outside the symbol is the average pilot rating.

High frequency airplanes. Looking first at Level 1 requirements for the high frequency configurations, they are seen to fit well except for $\boxed{9}$ which is rated 3.5, but is on the Level 2 boundary.

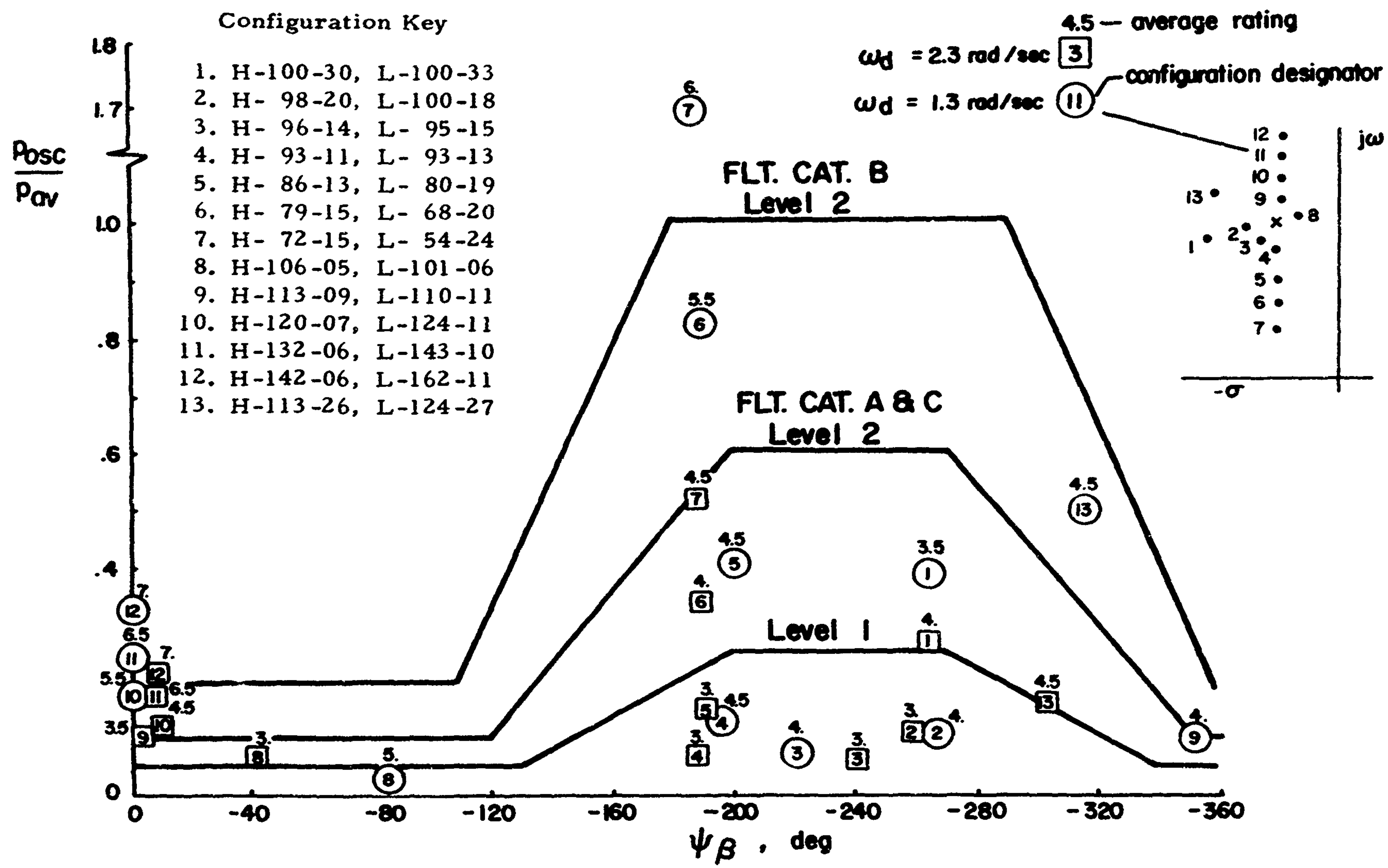


FIGURE IV-12 DATA COMPARISON WITH MIL-F-8785B (ASG) ROLL RATE OSCILLATION LIMITATIONS

For Level 2, the high frequency configurations do not fit well; the requirement is quite pessimistic in the neighborhood of $\psi_\beta = 0$, since $\boxed{10}$, rated 4.5 is slightly outside the boundary, and $\boxed{11}$, which should be close to the boundary with its 6.5 rating, has nearly twice the level of excitation allowed. It is also too conservative for the negative aileron yaw configurations ($\psi_\beta \doteq -180^\circ$), judging by $\boxed{7}$ which is on the Level 2 boundary with a 4.5 rating.

For small airplanes with reasonably high directional stability, say $\omega_d > 1.8$ rad/sec, the data would indicate that the Level 1 boundary for ψ_β between 0° and -130° could be raised to $\frac{p_{osc}}{p_{av}} \leq .10$ instead of .05; the Level 2 boundary could be raised to $\frac{p_{osc}}{p_{av}} = .15$ or even 0.20 for ψ_β between 0° and about -110°. The Flight Phase Category B, Level 2 boundary might be appropriate elsewhere, but data for $\frac{p_{osc}}{p_{av}} \doteq 1$ with $\psi_\beta = -180^\circ$ are needed to confirm this.

Low frequency airplanes. The low frequency configurations tested are seen not to fit the requirements whatsoever if the various levels are interpreted as levels of Cooper-Harper rating. All of the $\omega_d = 1.3$, $\zeta_d = 0.1$ configurations are rated worse than 3.5. (With $\zeta_d\omega_d = .13$ they do not quite meet the minimum Level 1, Phase C requirement that $\zeta_d\omega_d$ be greater than 0.15, either.)

Thinking strictly in terms of a Level 2 requirement for these low directional stability machines - that is, in terms of not allowing an already poor airplane to become unsafe for normal use - the military specification boundaries are clearly too restrictive. In the neighborhood of $\psi_\beta = 0$ the boundary could be as high as $\frac{p_{osc}}{p_{av}} = 0.25$ judging by Configuration (11); for negative aileron yaw airplanes ($\psi_\beta \doteq -180^\circ$), (6) is still flyable at

$\frac{p_{osc}}{p_{av}} = .80$. A slightly conservative boundary might be that for Flight Phase Category B, Level 2.

Suggested Civil Criterion

A "minimum level of safety for normal operations" criterion on roll-rate oscillations for small inputs might correspond to the Flight Phase Category B, Level 2 requirement shown in Figure IV-12. It is suggested that the $\frac{p_{osc}}{p_{av}} - \psi_{\beta}$ format be retained because of the relative ease of flight checking compared to other measures of Dutch roll excitation.

V. RESULTS AND DISCUSSION - SPIRAL STABILITY TESTS

The overall pilot rating for both the stable ($T_{\frac{1}{2}}$ = 7.7 sec) and unstable (T_2 = 8.7 sec) configurations was 3.5 in cruise and in climb. Although the rating was the same, the commentary indicated that it was not assigned for the same reasons in each case.

For general maneuvering in smooth air it was difficult to detect a difference in the two airplanes, which is not surprising since they had short roll mode time constants and identical Dutch roll mode characteristics. The difference in spiral stability was easily identified, however, by banking the airplane, centering the wheel, and noting the bank angle divergence or convergence.

In continuous turbulence, overall heading control was slightly easier with the stable airplane than with the unstable machine, but at no time did any real wandering take place with the latter, even during the distracting periods of clearance copying and frequency finding. Heading performance was certainly satisfactory at all times. However, the tendency to wander was there, and was the annoying factor which caused the spirally unstable airplane to be rated 3.5.

The factor which caused the stable airplane to be rated no better than 3.5 was its turbulence response - the large dihedral which was primarily responsible for the stable spiral also was responsible for continuous upsets in roll. If the pilot attempted to control bank angle tightly, the workload for the stable airplane was higher than for the unstable airplane; if he didn't close a tight roll loop the stable airplane wouldn't wander in heading as the unstable one would, but the ride was annoying.

No commentary was received which indicated that trim changes were a problem in the climb case.

The foregoing should not be interpreted as an absolute indication that spiral stability per se is a bad thing, and that instability is good. Certainly the test was far too brief to be definitive, and there is ample evidence from previous work to support the view that a moderate level of spiral stability is helpful (References 3 and 10 for example). Instead, it should be a reminder that it is important just how the spiral stability is obtained, and that the aerodynamic means available to the designer - large dihedral in particular, and low directional stability - may themselves degrade flying qualities in other areas. Use of simple wings-leveler devices can provide a useful level of spiral stability without leading to poor turbulence response.

VI. CONCLUSIONS

The following conclusions regarding roll mode time constant, roll control sensitivity, and Dutch roll mode excitation should be viewed in the context of small airplanes with moderate (L_β = -16 rad/sec^2/rad) dihedral effect and light Dutch roll damping (ζ_φ = 0.1), flown on an ILS approach with a visual runway lineup maneuver.

The conclusions regarding spiral stability apply to small airplanes in IFR climbing or cruising flight, with the level of stability determined by the amount of dihedral effect present.

Roll Mode Time Constant and Roll Control Sensitivity

1. The optimum combination of τ_{rm} and $L_{\delta a}$ is not sharply defined, but the "best" region from a design standpoint is centered upon τ_{rm} = .25 sec and $L_{\delta as}$ = 2 rad/sec^2/in or $L_{\delta aw}$ = 6 rad/sec^2/rad. A tentative conclusion, pending further work, is that the optimum force sensitivity is $L_{\delta a}$ = .5 rad/sec^2/lb for both stick and wheel.
2. There is a degradation of flying qualities for roll mode time constants smaller than τ_{rm} = .25 sec due to increased turbulence response in roll (this assumes that the higher roll damping is not obtained artificially).
3. The degradation in flying qualities for roll mode time constants longer than .25 seconds is associated with decreasing precision of roll control and a quality of "looseness" in roll which permits large upsets to develop.
4. These experiments are in good agreement with previous work for visual approaches as regards optimum levels of τ_{rm} and $L_{\delta as}$; however, they are less restrictive with respect to high sensitivities

for the longer roll mode time constants and with respect to low control power at short time constants, differences which are most likely due to the better roll rate and bank angle cues available in the visual task.

5. The dihedral level (L_{β} = -16 rad/ sec^2/ rad) used in the tests was possibly a factor in the two-unit rating degradation in going from τ_{rm} = .25 sec to τ_{rm} = 1.0 sec with optimum $I_{\delta a}$. Comparison with other data indicates that L_{β} = -8 would be close to optimum for the longer time constants, and might result in a one-unit improvement.
6. The results tend to confirm, in general, the new military requirements for the handling qualities of this category of airplane. However, they also indicate that for long, but still permissible, roll time constants, the minimum roll performance requirements could be met with a level of control power which would be too low for safe operation. A requirement for a minimum level of roll acceleration capability for each flying qualities level is needed.
7. The evidence is sufficient to suggest minimum requirements for safe, normal operation of small general purpose airplanes, as follows:
   (a) The roll mode time constant should be no longer than 1.4 seconds.
   (b) The roll control power should be sufficient to provide at least a 30° change in bank angle in two seconds or, alternatively, a 60° change in four seconds. If the roll mode time constant is greater than .15 seconds, a requirement for a roll acceleration capability of at least 1.5 rad/ sec^2 should be governing.
   (c) The maximum stick or wheel force needed to meet the roll performance requirements should not exceed 20 pounds.
   (d) The roll response sensitivity should not be greater than that which gives 60° change in bank angle in two seconds per pound of stick or wheel force.

(e) For mechanical control systems the wheel throw should not be greater than $\pm 80^{o}$.

Dutch Roll Excitation

1. Airplanes with moderate Dutch roll frequency (ω_d greater than 2.0 rad/sec) are more tolerant of variations in aileron yaw ($N_{\delta a}$) and yaw due to roll rate (N_p) than those with lower directional stability. For the higher frequency case, the "best" level of flying qualities is obtained for zero or slightly negative $N_{\delta a}$ and small positive N_p.

2. For low Dutch roll frequency airplanes (ω_d less than 1.5 rad/sec), the best handling qualities are obtained with moderate positive aileron yaw and zero or slightly negative yaw due to roll rate. This combination allows the pilot to coordinate roll control and rudder pedal inputs in the normal sense - right stick and right rudder, for example - without inducing the large sideslips to which these weak directional stability airplanes are prone.

3. Large amounts of positive aileron yaw (that is, large enough to make $\omega_\varphi/\omega_d > 1.3$) lead to a serious degradation of flying qualities in terms of poor bank angle and heading control, the need for unnatural stick and rudder co-ordination - right stick and left rudder - and in the extreme, pilot-airplane instability.

4. Large amounts (sufficient to make $\omega_\varphi/\omega_d < .8$) of negative aileron yaw are not so detrimental as positive yaw, since the stick and rudder coordination required to counter them is natural. However, the presence of adverse yaw will degrade roll performance if rudder is not used, to the point of making the airplane nearly uncontrollable in extreme cases.

5. There is a notable difference between pilots in their ability to handle moderate and large amounts of Dutch roll excitation. At best, the pilot is

able to work the controls almost independently, handling roll problems with the stick and sideslip and yaw with the rudder, regardless of the origin of the upsets; at worst he will always move the stick and rudder in the same direction, which accentuates the upsets associated with moderate or large amounts of positive aileron yaw. Practice and proper technique tend to improve ratings on a given configuration, but a pilot may still find the workload high with large Dutch roll excitation present.

6. The results lend confirmation to newly proposed military specification for allowable roll rate oscillations for this category of airplane (Class I, Flight Phase Category C) only for the case of high Dutch roll frequency and even then only for the highest level (Level 1) of flying qualities. The Level 2 requirement is too restrictive, and the requirement as posed does not fit the low Dutch roll frequency case at all. A new Level 2 requirement based on the Flight Phase Category B, Level 2, boundary is proposed.

7. The evidence is sufficient to suggest that minimum criteria for the safe, normal operation of small general aviation airplanes should include limits on permissible roll rate oscillations following small roll control inputs. The format of the military requirement is suitable, and the boundaries should correspond to those of Flight Phase Category B, Level 2.

Spiral Stability

1. Both moderately stable ($T_{\frac{1}{2}}$ = 7.7 sec) and unstable (T_2 = 7.8 sec) spiral modes are acceptable for the IFR climb and cruise task.

2. The unstable machine exhibits a tendency to wander in heading, but this level of divergence does not interfere with the carrying out of normal IFR duties. Heading tracking is slightly easier when the mode has moderate stability.

3. The manner in which spiral stability is obtained is important to the overall flying qualities of the airplane. Large dihedral, for example, as used in this test, leads to large roll upsets in turbulence, a factor which can add to the pilot's workload and, on the whole, be as annoying as the poor unattended flight characteristics of a spirally unstable airplane.

REFERENCES

1. Ellis, D. R. and Seckel, E., Flying Qualities of Small General Aviation Airplanes. Part 1. The Influence of Dutch Roll Frequency, Dutch Roll Damping, and Dihedral Effect, FAA Report No. DS-69-8, June 1969, Princeton University Report No. 870, June 1969.

2. Anon. Spiral Stability and Stall Deterrent Devices for Small Airplanes, Advance Notice of Proposed Rule Making No. 67-32, FAA.

3. Hall, G. W., An In-Flight Investigation of Lateral-Directional Dynamics for Cruising Flight, FAA ADS 69-13, December 1969.

4. Seckel, E., Miller, G. E., and Nixon, W. B., Lateral-Directional Flying Qualities for Power Approach, Princeton University Report No. 727, September 1966.

5. Ashkenas, I. L., A Study of Conventional Airplane Handling Qualities Requirements, Part 1, Roll Handling Qualities, AFFDL-TR-65-138, Part 1, November 1965.

6. Meeker, J. I. and Hall, G. W., In-Flight Evaluation of Lateral-Directional Handling Qualities for the Fighter Mission, AFFDL-TR-67-98, October 1967.

7. Ashkenas, I. L., A Study of Conventional Airplane Handling Qualities Requirements, Part II. Lateral-Directional Oscillatory Handling Qualities, AFFDL-TR-65-138, Part II, November 1965.

8. Chalk, C. R., Neal, T. P., Harris, T. M., Pritchard, F. E., and Woodcock, R. J., Background Information and User Guide for MIL-F-8785B(AS6), "Military Specification - Flying Qualities of Piloted Airplanes," AFFDL-TR-69-72, August 1969.

9. Ashkenas, I. L. and McRuer, D. T., Approximate Airframe Transfer Functions and Application to Single Sensor Control Systems, WADC TR 58-82, June 1958.

10. Driscoll, N. R., Effects of a Simple Stability Augmentation System on the Performance of Non-Instrument Qualified Light-Aircraft Pilots During Instrument Flight, NASA TN D-3970, 1967.

11. Seckel, E., Franklin, J. A., and Miller, G. E., Lateral-Directional Flying Qualities for Power Approach: Influence of Dutch-roll Frequency, Princeton University Report No. 797, September 1967.

12. Cooper, G. E. and Harper, R. P., Jr., The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities, NASA TN D-5153, April 1969.

13. Anon: Military Specification, Flying Qualities of Piloted Airplanes, MIL-F-8785B(ASG), 7 August 1969.

14. British Civil Airworthiness Requirements, Air Registration Board, London.

15. Pinsker, W. J. G., Directional Stability In Flight with Bank Angle Constraint as a Condition Defining a Minimum Acceptable Value for N_v, R&M No. 3556, 1968.

16. Federal Aviation Regulations, Volume III, Part 23, Airworthiness Standards: Normal, Utility, and Acrobatic Category Airplanes, Department of Transportation, Federal Aviation Administration, December 1969.

TABLE 3

DERIVATIVE AND PARAMETER VALUES FOR ROLL DAMPING AND ROLL CONTROL SENSITIVITY EXPERIMENTS

Conf.	τ_{rm}	$\frac{\omega_\varphi}{\omega_d}$	ζ_φ	$\zeta_\varphi \omega_\varphi$	$\frac{K_d}{K_{ss}}$	L_β	L_p	L_r	N_β	N_r	N_p	$N_{\delta a}$
R1	.1	.97	.11	.24	.054	-15.97	-9.97	.75	4.97	-.234	.01	0
R2	.25	.96	.14	.30	.13	-16.8	-3.84	1.32	4.67	-.366	.01	0
R3	.50	.97	.17	.38	.108	-16.02	-1.7	1.66	4.87	-.506	.05	0
R4	1.0	1.00	.21	.49	.094	-16.08	-.48	2.28	5.19	-.726	.01	0

ω_d = 2.3 rad/sec

$\zeta_d = 0.10$

$\frac{Y_\beta}{V} = -.25$

$L_{\delta r} = 0$

TABLE 4

DERIVATIVE AND PARAMETER VALUES FOR DUTCH ROLL EXCITATION EXPERIMENTS

Configuration* $\omega_d - \frac{\omega_\varphi}{\omega_d} - \zeta_\varphi$	$\zeta_\varphi \omega_\varphi$	$\frac{K_d}{K_{ss}}$	L_β	L_p	L_r	N_β	N_r	N_p	$N_{\delta a}$	$\frac{N_{\delta a}}{L_{\delta a}}$
L - 54 - 24	16	2.2	-16.18	-3.83	2.36	1.17	-.171	.05	-1.25	-.043
L - 68 - 20	18	1.2	-16.18	-3.83	2.36	1.17	-.171	.05	- .75	-.026
L - 80 - 19	20	.59	-16.17	-3.84	2.36	1.174	-.171	.05	- .25	-.009
L - 93 - 13	15	.15	-16.04	-3.95	.57	1.577	-.056	.15	- .25	-.009
L - 95 - 15	18	.13	-16.40	-3.92	.94	1.50	-.086	.13	0	0
L - 100 - 18	23	.16	-16.18	-3.84	2.36	1.174	-.171	.05	.75	.026
L - 100 - 33	42	.43	-16.00	-3.75	2.0	.60	-.39	-.10	1.75	.06
L - 101 - 06	07	.10	-15.91	-4.11	-.86	1.93	.104	.25	- .25	-.009
L - 110 - 11	16	.18	-16.04	-3.95	.57	1.577	-.056	.15	.75	.026
L - 124 - 11	17	.35	-16.04	-3.95	.57	1.577	-.056	.15	1.75	.06
L - 124 - 27	44	.43	-16.00	-3.75	2.0	.60	-.39	-.05	3.42	.118
L - 143 - 10	18	.49	-16.04	-3.95	.57	1.58	-.056	.15	3.25	.112
L - 162 - 11	22	.62	-16.04	-3.95	.57	1.58	-.056	.15	5.25	.181

*ω_d = 1.3 rad/sec ≡ L

τ_{rm} = .25 sec

$\frac{\omega_\varphi}{\omega_d}$, ζ_φ, $\zeta_\varphi \omega_\varphi$ x 100

$\frac{K_d}{K_{ss}}$ overlays on Figures IV-2 and IV-3

TABLE 4 (continued)

Configuration* $\omega_d - \frac{\omega_\varphi}{\omega_d} - \zeta_\varphi$	$\zeta_\varphi \omega_\varphi$	$\frac{K_d}{K_{ss}}$	L_β	L_p	L_r	N_β	N_r	N_p	$N_{\delta a}$	$\frac{N_{\delta a}}{L_{\delta a}}$
H - 72 - 15	25	.90	-15.93	-3.81	1.41	4.48	-.396	-.05	-3.25	-.112
H - 79 - 15	27	.60	-15.93	-3.81	1.41	4.48	-.396	-.05	-2.25	-.078
H - 86 - 13	25	.35	-16.15	-3.88	1.10	4.83	-.331	.05	-1.75	-.06
H - 93 - 11	24	.17	-16.32	-3.95	.81	5.172	-.256	.15	-1.25	-.043
H - 96 - 14	30	.13	-16.80	-3.84	1.32	4.67	-.366	.01	0	0
H - 98 - 20	45	.22	-15.99	-3.71	2.15	3.683	-.496	-.25	2.25	.078
H -100 - 30	69	.38	-16.00	-3.47	2.0	2.35	-.81	-.60	4.88	.174
H -106 - 05	13	.12	-15.70	-4.20	.02	6.04	-.006	.45	.25	-.009
H -113 - 09	23	.19	-15.27	-4.03	.49	5.475	-.176	.25	2.25	.078
H -113 - 26	67	.34	-16.00	-3.68	2.57	3.24	-.521	-.35	6.25	.215
H -120 - 07	20	.28	-15.83	-4.12	.25	5.77	-.091	.35	3.25	.112
H -132 - 06	20	.38	-15.83	-4.12	.25	5.77	-.091	.35	6.25	.215
H -142 - 06	20	.45	-15.83	-4.12	.25	5.77	-.091	.35	8.75	.302

*ω_d = 2.3 rad/sec ≡ H

$\frac{\omega_\varphi}{\omega_d}$, ζ_φ, $\zeta_\varphi \omega_\varphi$ × 100

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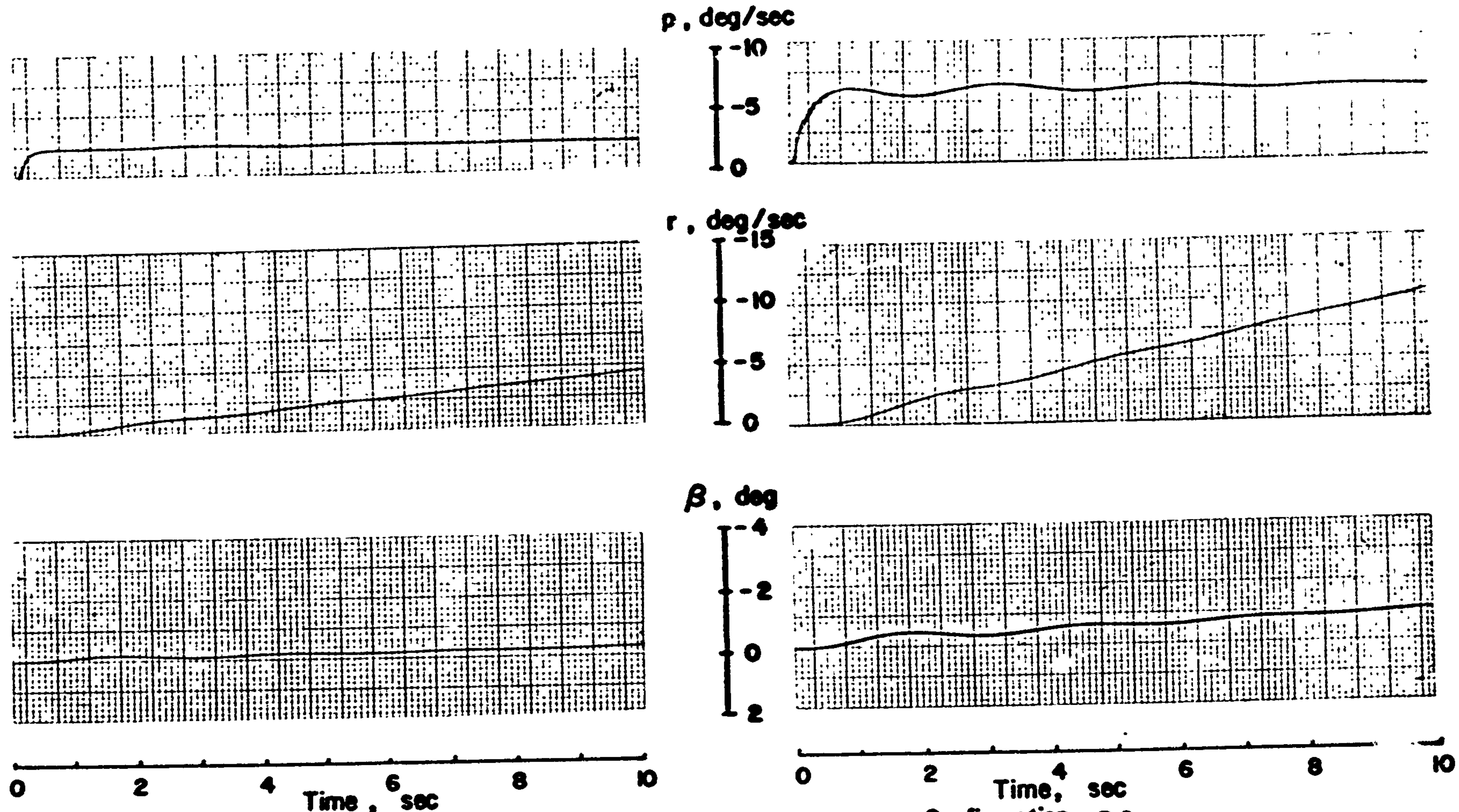
APPENDIX

RESPONSES TO LEFT ROLL CONTROL STEP INPUTS

Note: $\frac{\delta a}{2}$ indicates half-nominal input used to reduce size of response.



Configuration R1

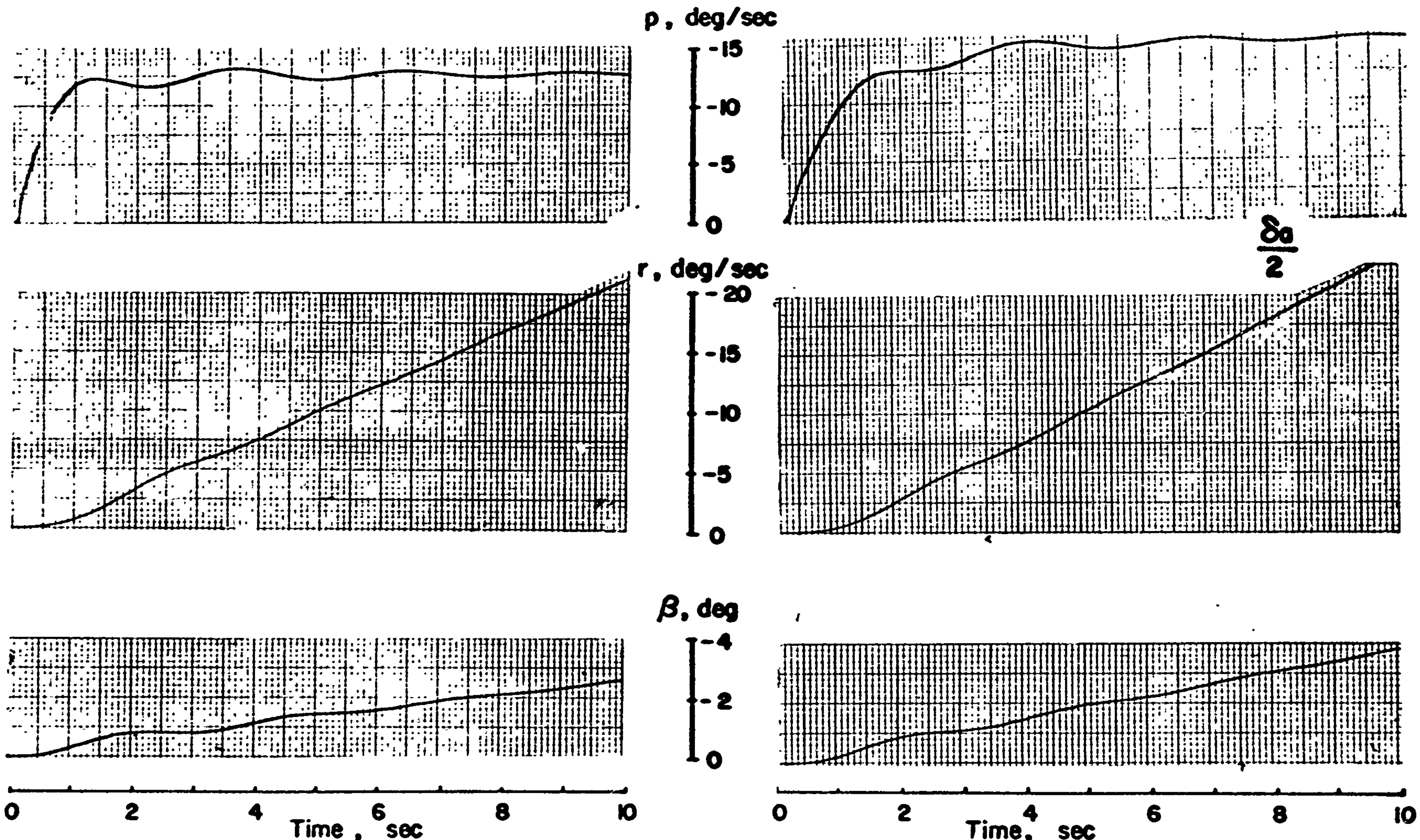
$\omega_\phi = 2.18$, $\zeta_\phi = .11$, $\omega_d = 2.3$, $\zeta_d = .1$

$N_p = .01$, $N\delta a / L\delta a = 0$, $\tau_{rm} = .1$

Configuration R2

$\omega_\phi = 2.14$, $\zeta_\phi = .14$, $\omega_d = 2.3$, $\zeta_d = .1$

$N_p = .01$, $N\delta a / L\delta a = 0$, $\tau_{rm} = .25$



Configuration R 3

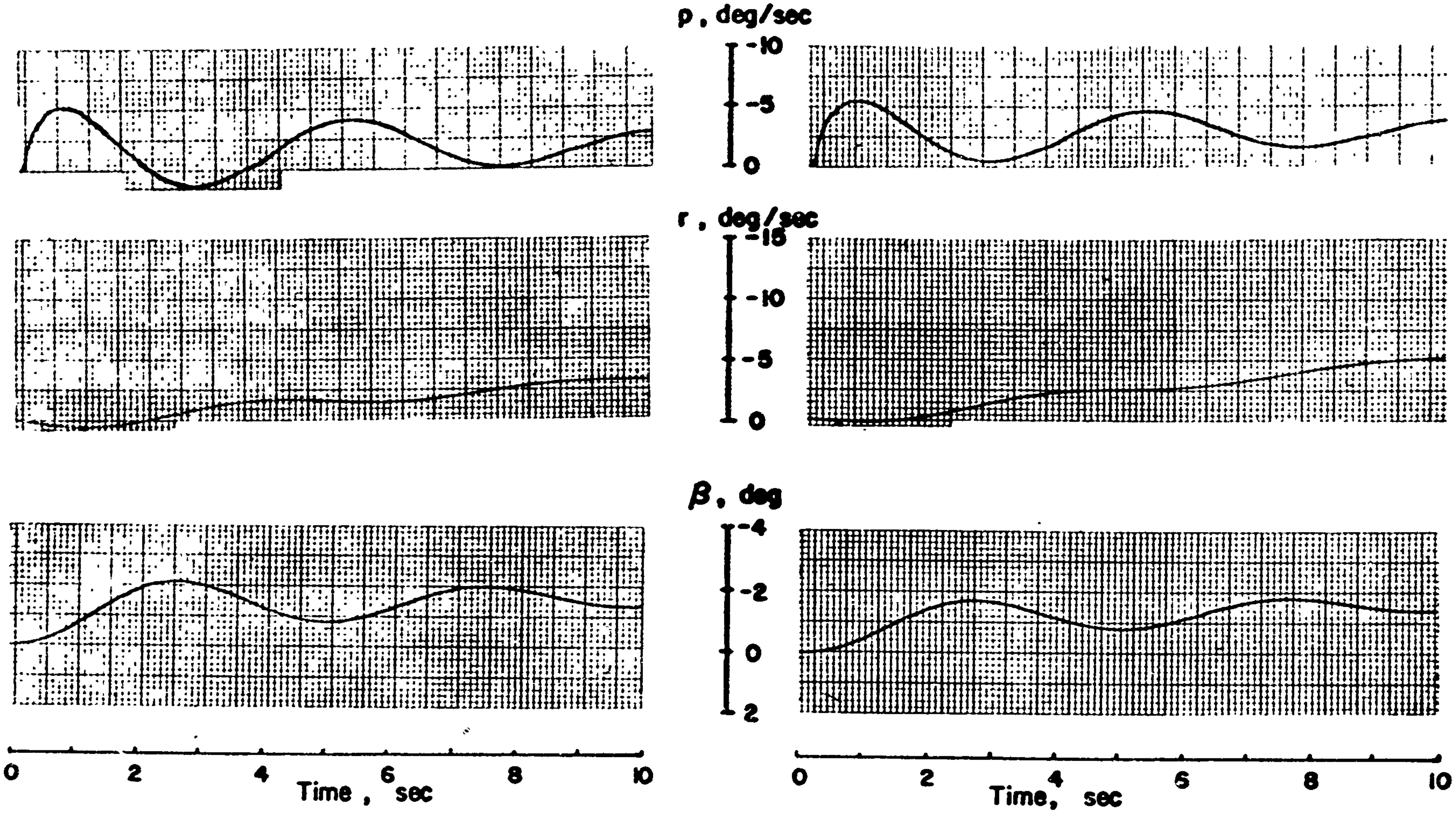
$\omega_\phi = 2.24$, $\zeta_\phi = .17$, $\omega_d = 2.3$, $\zeta_d = .1$

$N_p = .05$, $N\delta_a / L\delta_a = 0$, $\tau_{rm} = .5$

Configuration R 4

$\omega_\phi = 2.33$, $\zeta_\phi = .21$, $\omega_d = 2.3$, $\zeta_d = .1$

$N_p = .01$, $N\delta_a / L\delta_a = 0$, $\tau_{rm} = 1.0$



Configuration L-54-24

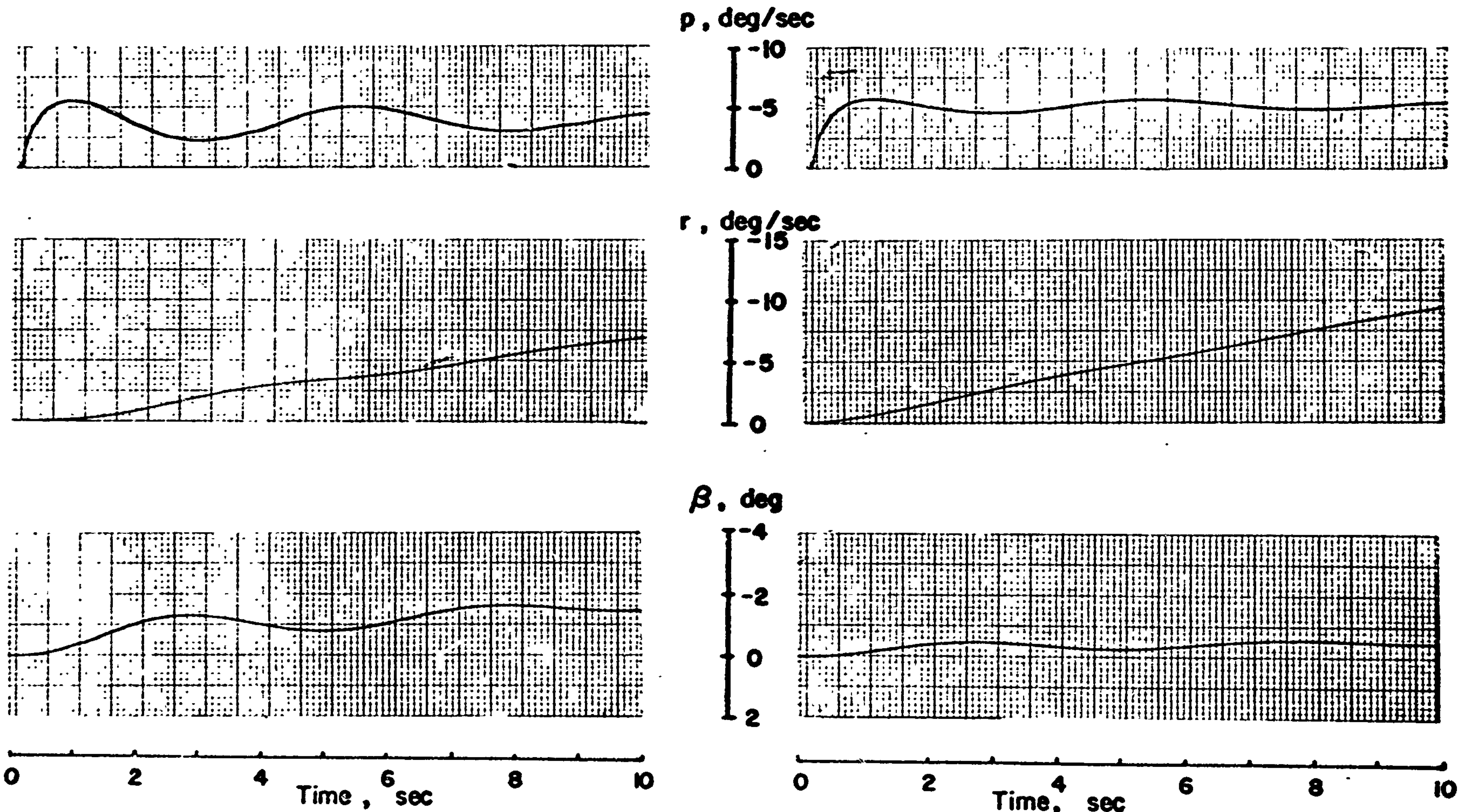
$\omega_\phi = .70$, $\zeta_\phi = .24$, $\omega_d = 1.3$, $\zeta_d = .1$

$N_p = .05$, $N_{\delta a}/L_{\delta a} = -.043$, $\tau_{rm} = .25$

Configuration L-68-20

$\omega_\phi = .88$, $\zeta_\phi = .20$, $\omega_d = 1.3$, $\zeta_d = .1$

$N_p = .05$, $N_{\delta a}/L_{\delta a} = -.026$, $\tau_{rm} = .25$



Configuration L - 80 - 19

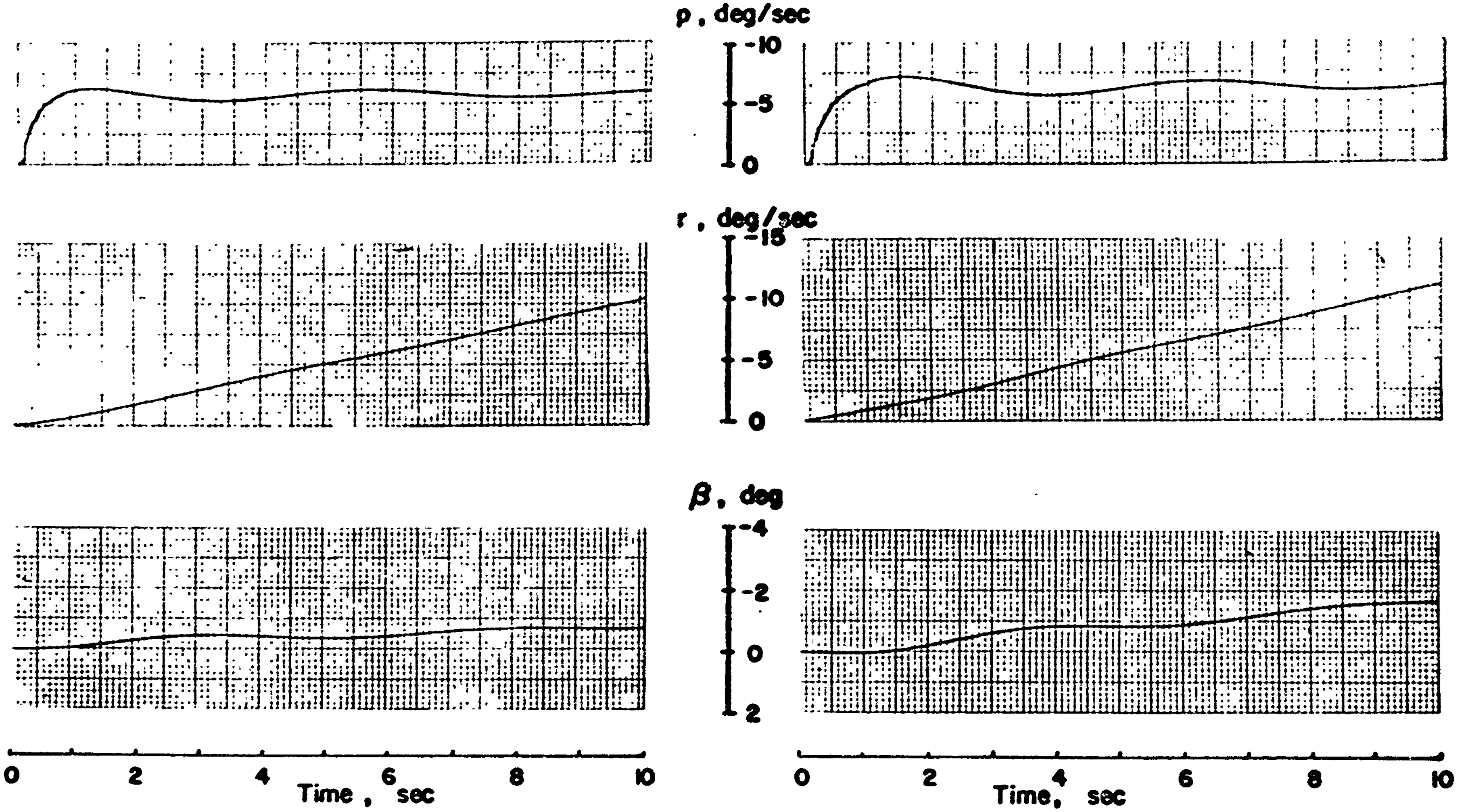
$\omega_\phi = 1.04$, $\zeta_\phi = .19$, $\omega_d = 1.3$, $\zeta_d = .1$

$N_p = .05$, $N\delta_a / L\delta_a = -.009$, $\tau_{rm} = .25$

Configuration L - 93 - 13

$\omega_\phi = 1.21$, $\zeta_\phi = .13$, $\omega_d = 1.3$, $\zeta_d = .1$

$N_p = .15$, $N\delta_a / L\delta_a = -.009$, $\tau_{rm} = .25$



Configuration L - 95 - 15

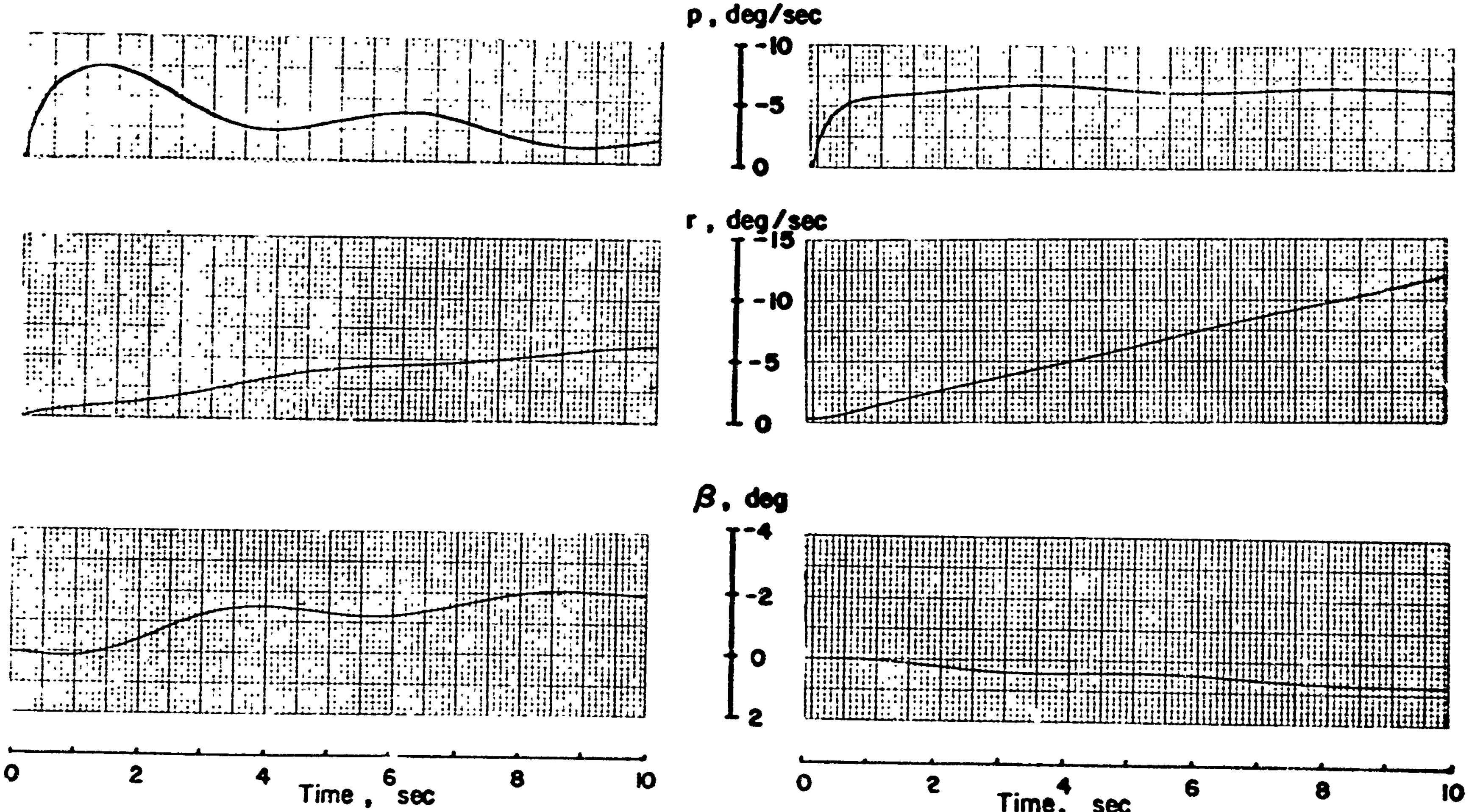
$\omega_\phi = 1.23$, $\zeta_\phi = .15$, $\omega_d = 1.3$, $\zeta_d = .1$

$N_p = .13$, $N_{\delta a}/L_{\delta a} = 0$, $\tau_{rm} = 25$

Configuration L - 100 - 18

$\omega_\phi = 1.3$, $\zeta_\phi = .18$, $\omega_d = 1.3$, $\zeta_d = .1$

$N_p = .05$, $N_{\delta a}/L_{\delta a} = .026$, $\tau_{rm} = .25$



Configuration L - 100 - 33

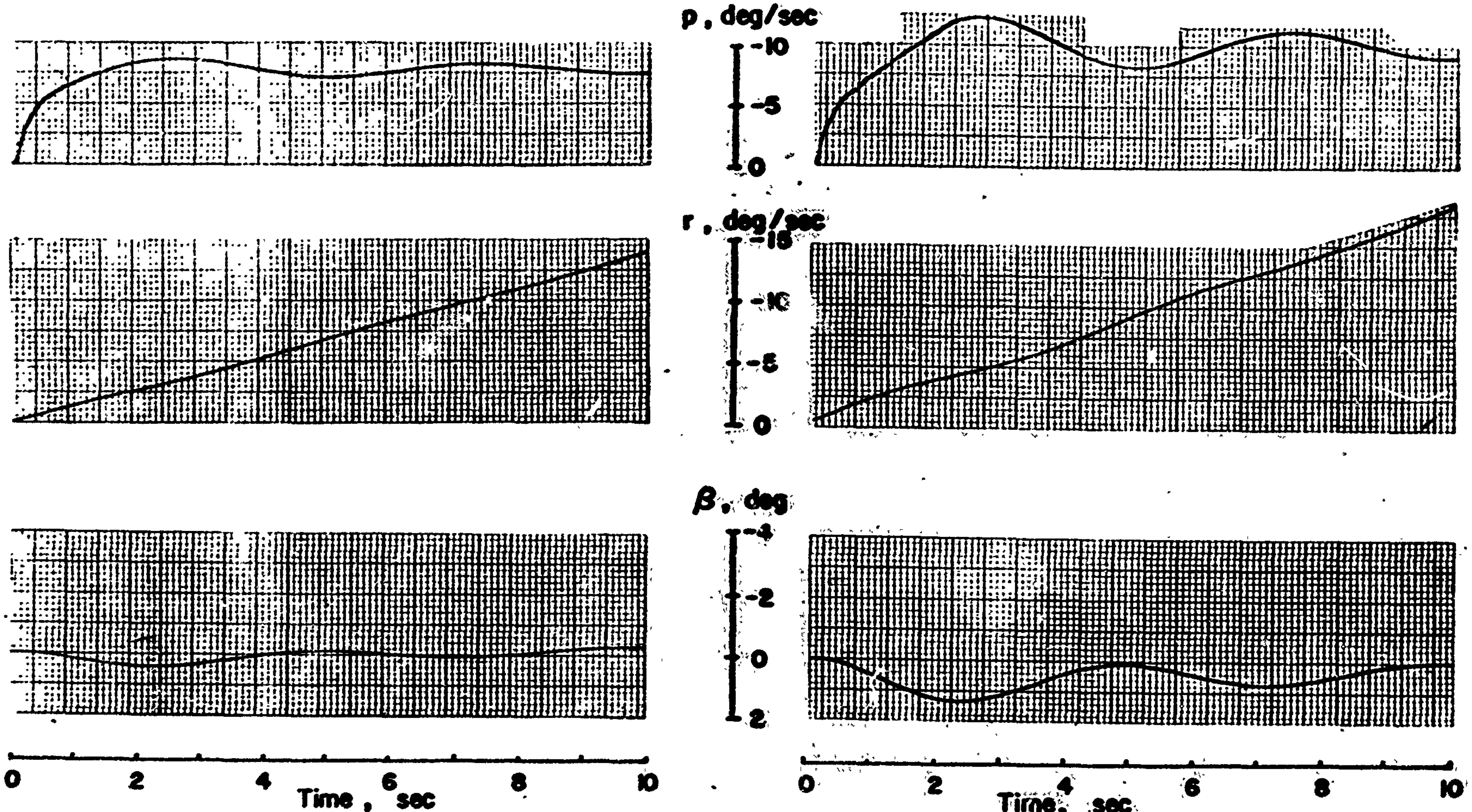
$\omega_\phi = 1.3$, $\zeta_\phi = .33$, $\omega_d = 1.3$, $\zeta_d = .1$

$N_p = -10$, $N_{\delta a}/L_{\delta a} = .06$, $\tau_{rm} = .25$

Configuration L - 101 - 06

$\omega_\phi = 1.31$, $\zeta_\phi = .06$, $\omega_d = 1.3$, $\zeta_d = .1$

$N_p = .25$, $N_{\delta a}/L_{\delta a} = -.009$, $\tau_{rm} = .25$



Configuration L-110-11

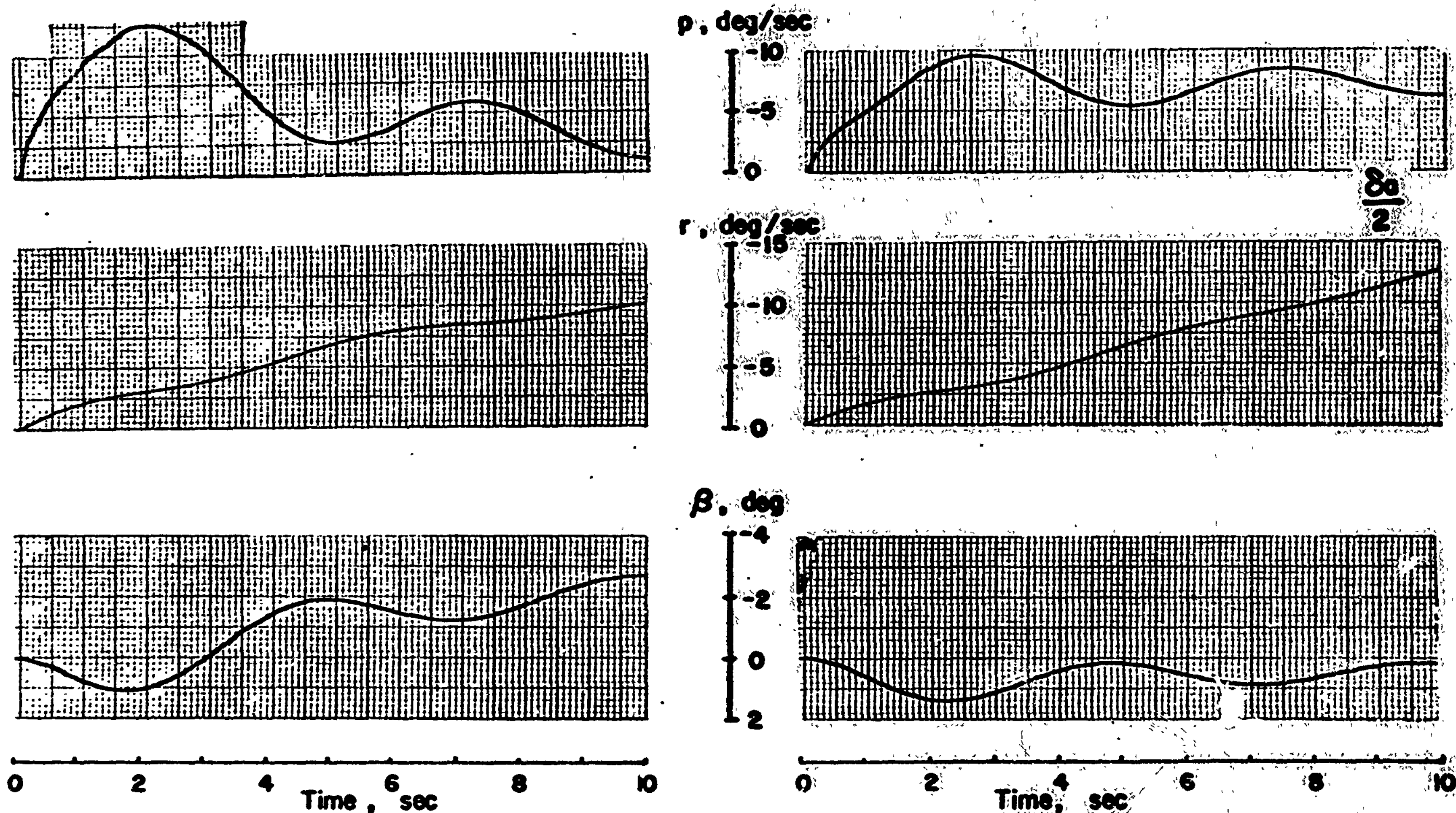
$\omega_\phi = 1.43$, $\zeta_\phi = .11$, $\omega_d = 1.3$, $\zeta_d = .1$

$N_p = .15$, $N_{\delta a}/L_{\delta a} = .026$, $\tau_{rm} = .25$

Configuration L-124-11

$\omega_\phi = 1.61$, $\zeta_\phi = .11$, $\omega_d = 1.3$, $\zeta_d = .1$

$N_p = .15$, $N_{\delta a}/L_{\delta a} = .06$, $\tau_{rm} = .25$



Configuration L - 124 - 27

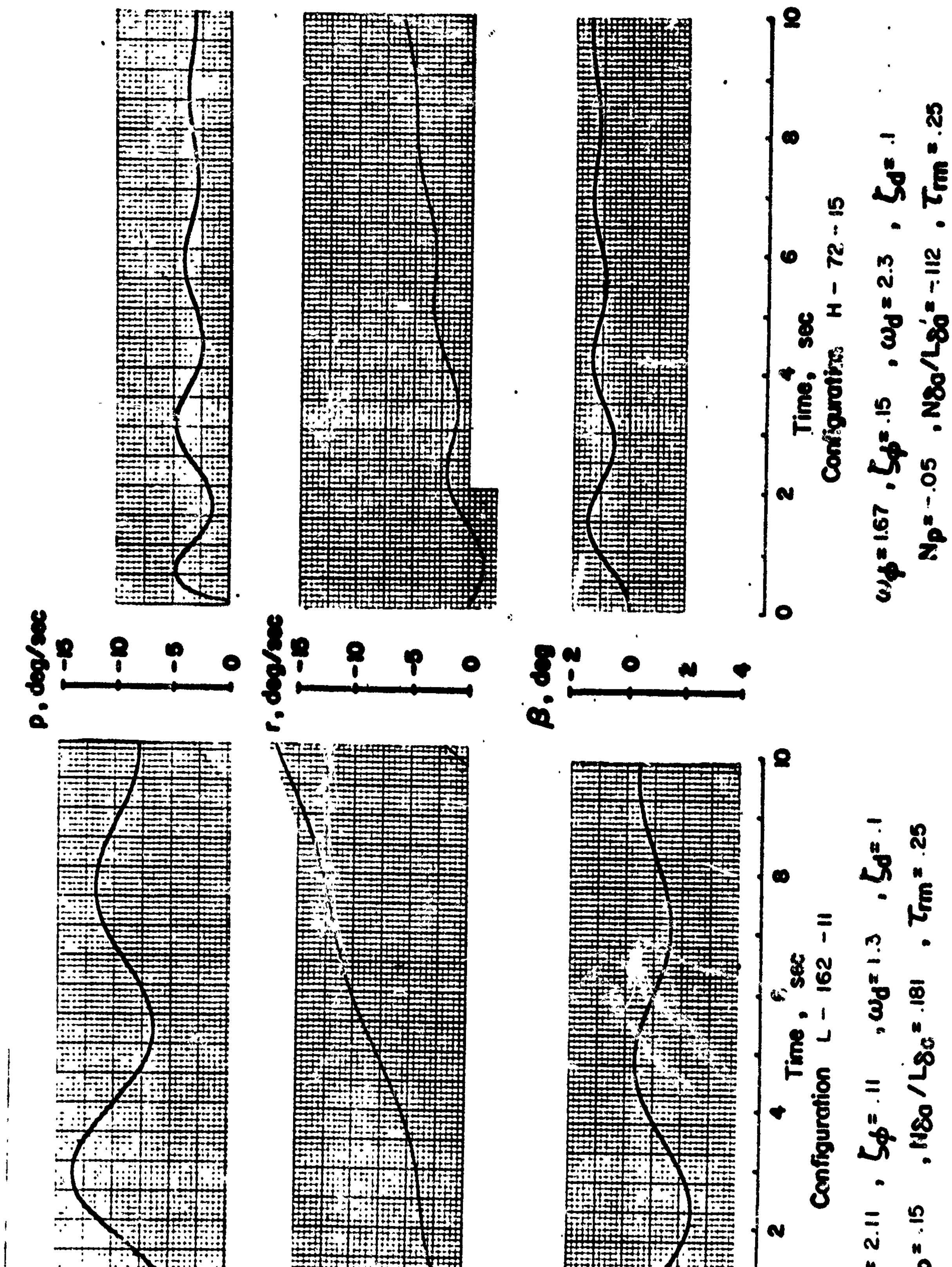
$\omega_\phi = 1.61$, $\zeta_\phi = .27$, $\omega_d = 1.3$, $\zeta_d = .1$

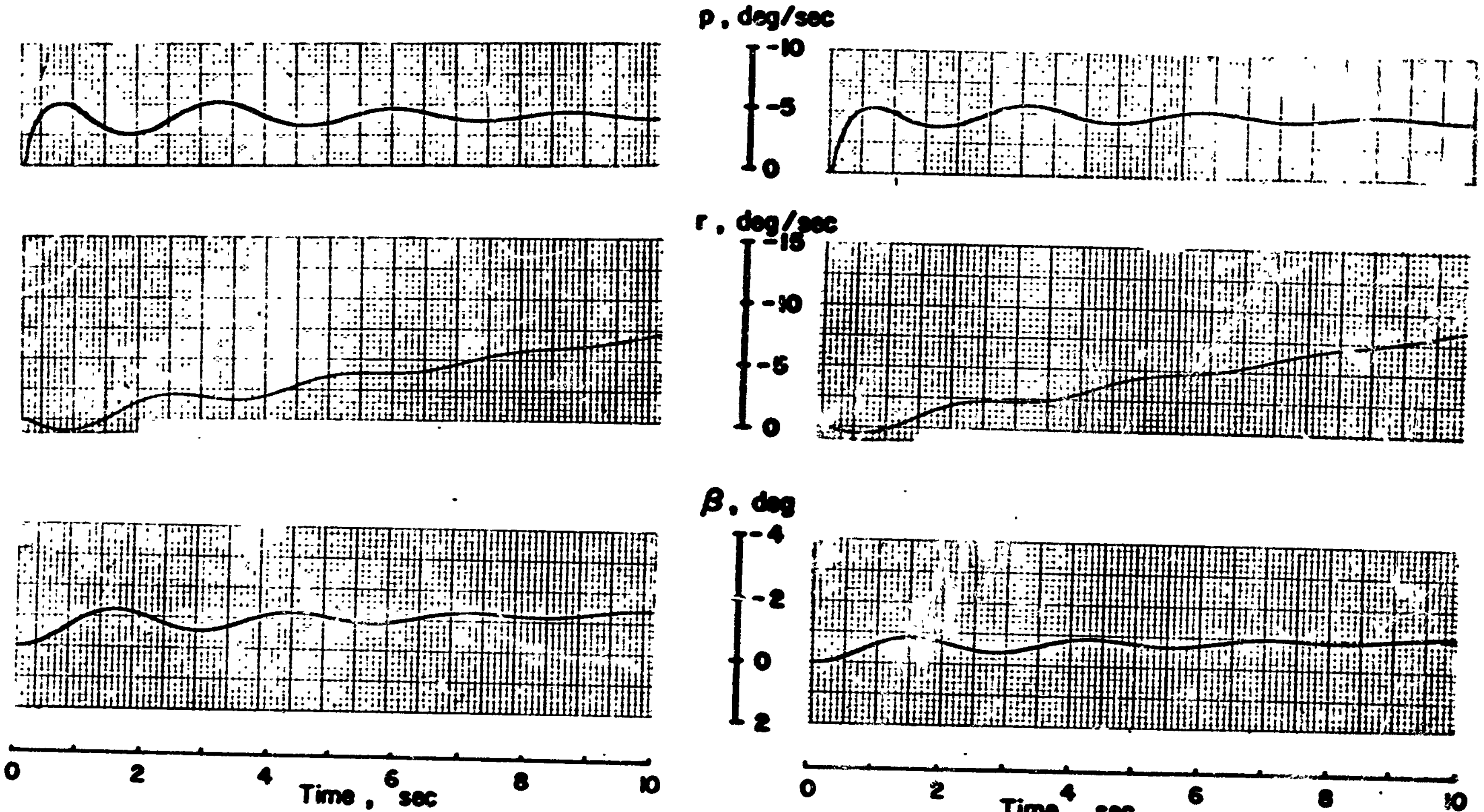
$N_p = -.05$, $N_{\delta a}/L_{\delta a} = .118$, $\tau_{rm} = .25$

Configuration L - 143 - 10

$\omega_\phi = 1.86$, $\zeta_\phi = .10$, $\omega_d = 1.3$, $\zeta_d = .1$

$N_p = .15$, $N_{\delta a}/L_{\delta a} = .112$, $\tau_{rm} = .25$


p, deg/sec
-15
-10
-5
0
r, deg/sec
-15
-10
-5
0
β, deg
-2
0
2
4
Time, sec
0
2
4
6
8
10
Configuration L - 162 - 11
ωφ = 2.11 , ζφ = .11 , ωd = 1.3 , ζd = .1
Np = .15 , Nδa / Lδa = .181 , τrm = .25
Configuration H - 72 - 15
ωφ = 1.67 , ζφ = .15 , ωd = 2.3 , ζd = .1
Np = -.05 , Nδa/L'δa = -.112 , τrm = .25



Configuration H - 79 - 15

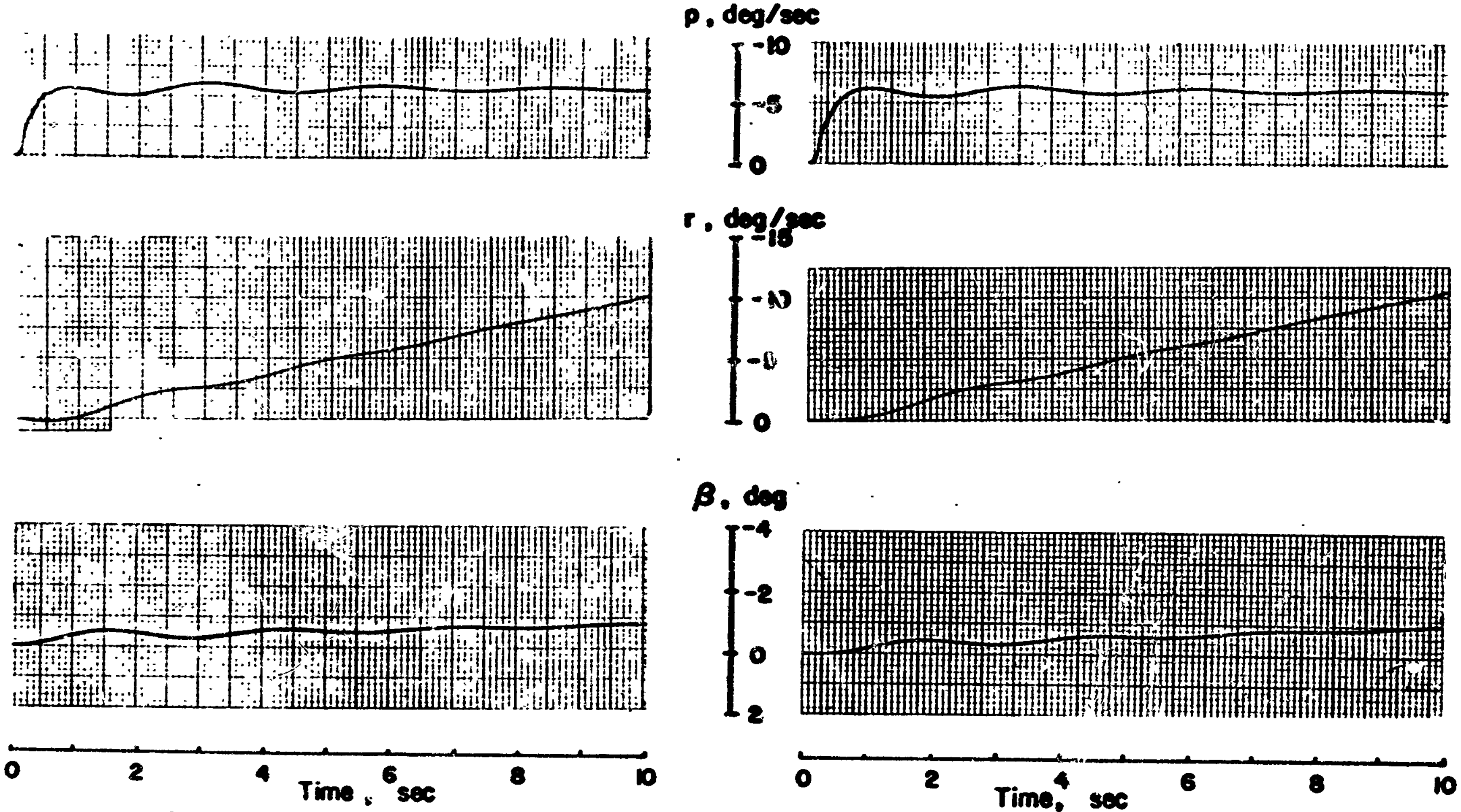
$\omega_\phi = 1.82$, $\zeta_\phi = .15$, $\omega_d = 2.3$, $\zeta_d = .1$

$N_p = -.05$, $N_{\delta a}/L_{\delta a} = -.078$, $\tau_{rm} = .25$

Configuration H - 86 - 13

$\omega_\phi = 1.98$, $\zeta_\phi = .13$, $\omega_d = 2.3$, $\zeta_d = .1$

$N_p = .05$, $N_{\delta a}/L_{\delta a} = -.060$, $\tau_{rm} = .25$



Configuration H-93-11

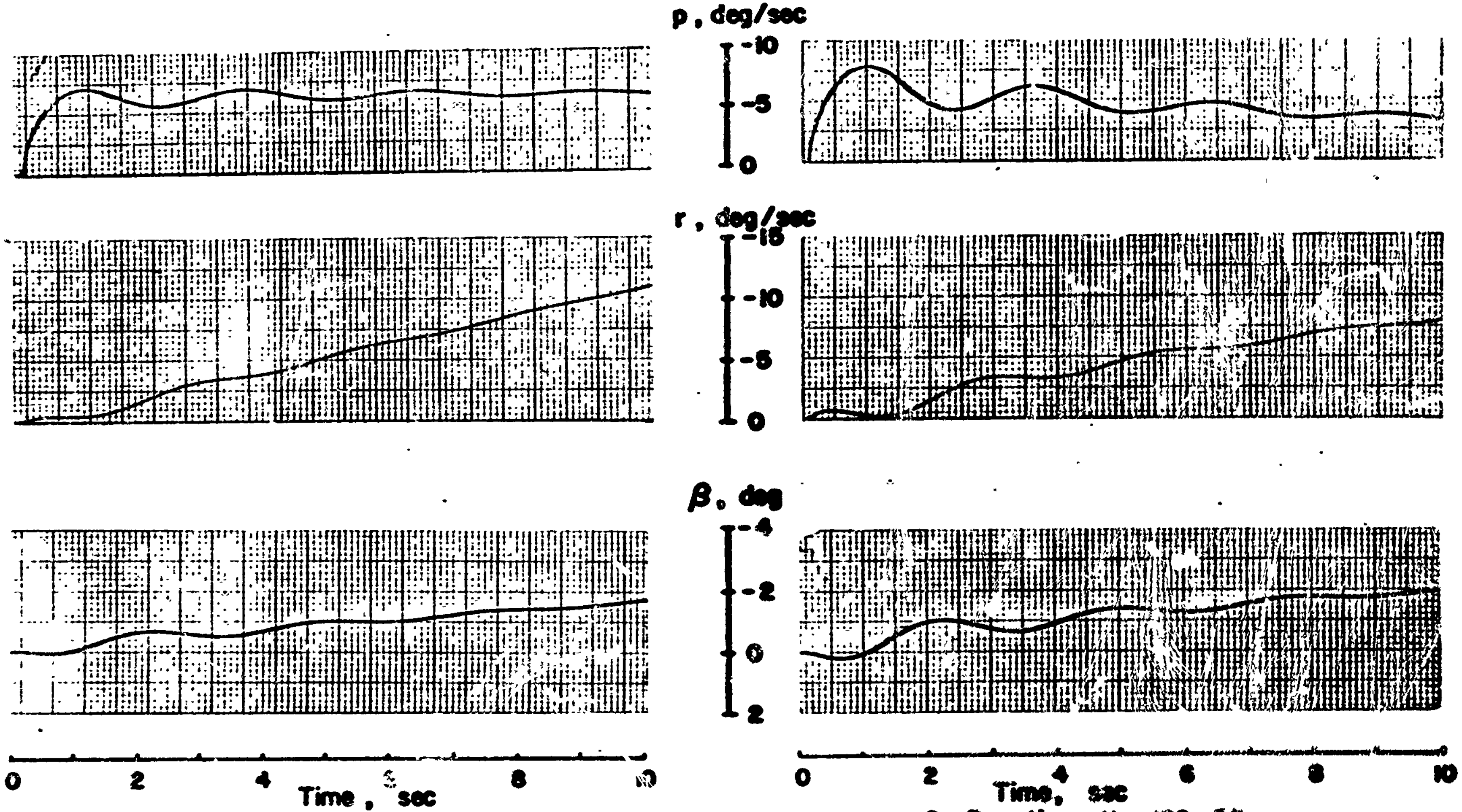
$\omega_\phi = 2.14$, $\zeta_\phi = .11$, $\omega_d = 2.3$, $\zeta_d = .1$

$N_p = .15$, $N_{\delta a}/L_{\delta a} = -.043$, $\tau_{rm} = .25$

Configuration H-96-14

$\omega_\phi = 2.14$, $\zeta_\phi = .14$, $\omega_d = 2.3$, $\zeta_d = .1$

$N_p = .01$, $N_{\delta a}/L_{\delta a} = 0$, $\tau_{rm} = .25$



Configuration H - 98 - 20

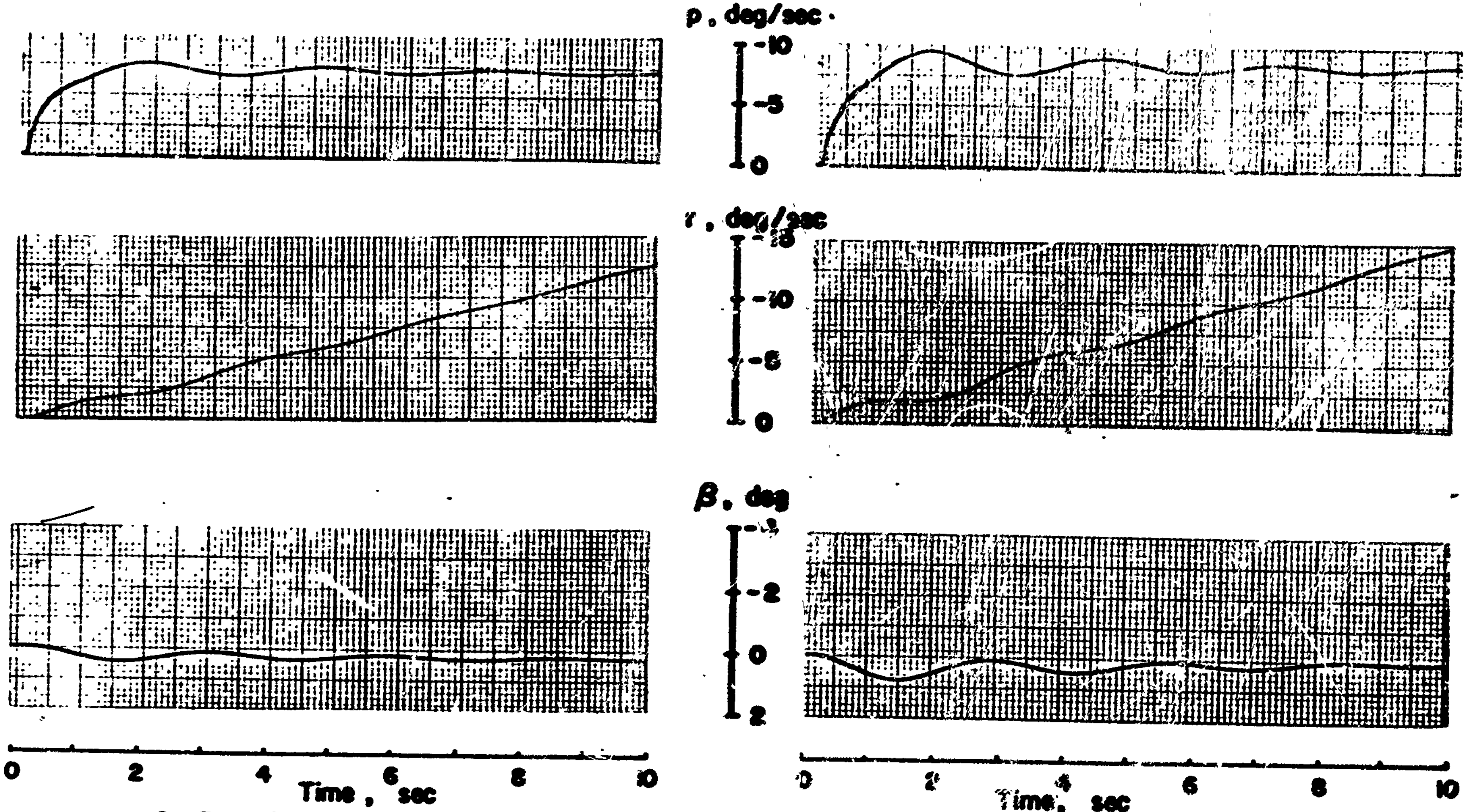
$\omega_\phi = 2.26$, $\zeta_\phi = .20$, $\omega_d = 2.3$, $\zeta_d = .1$

$N_p = -.25$, $N_{\delta a}/L_{\delta a} = .078$, $\tau_{rm} = .25$

Configuration H - 100 - 30

$\omega_\phi = 2.30$, $\zeta_\phi = .30$, $\omega_d = 2.3$, $\zeta_d = .1$

$N_p = -.60$, $N_{\delta a}/L_{\delta a} = .174$, $\tau_{rm} = .25$



Configuration H - 106 - 05

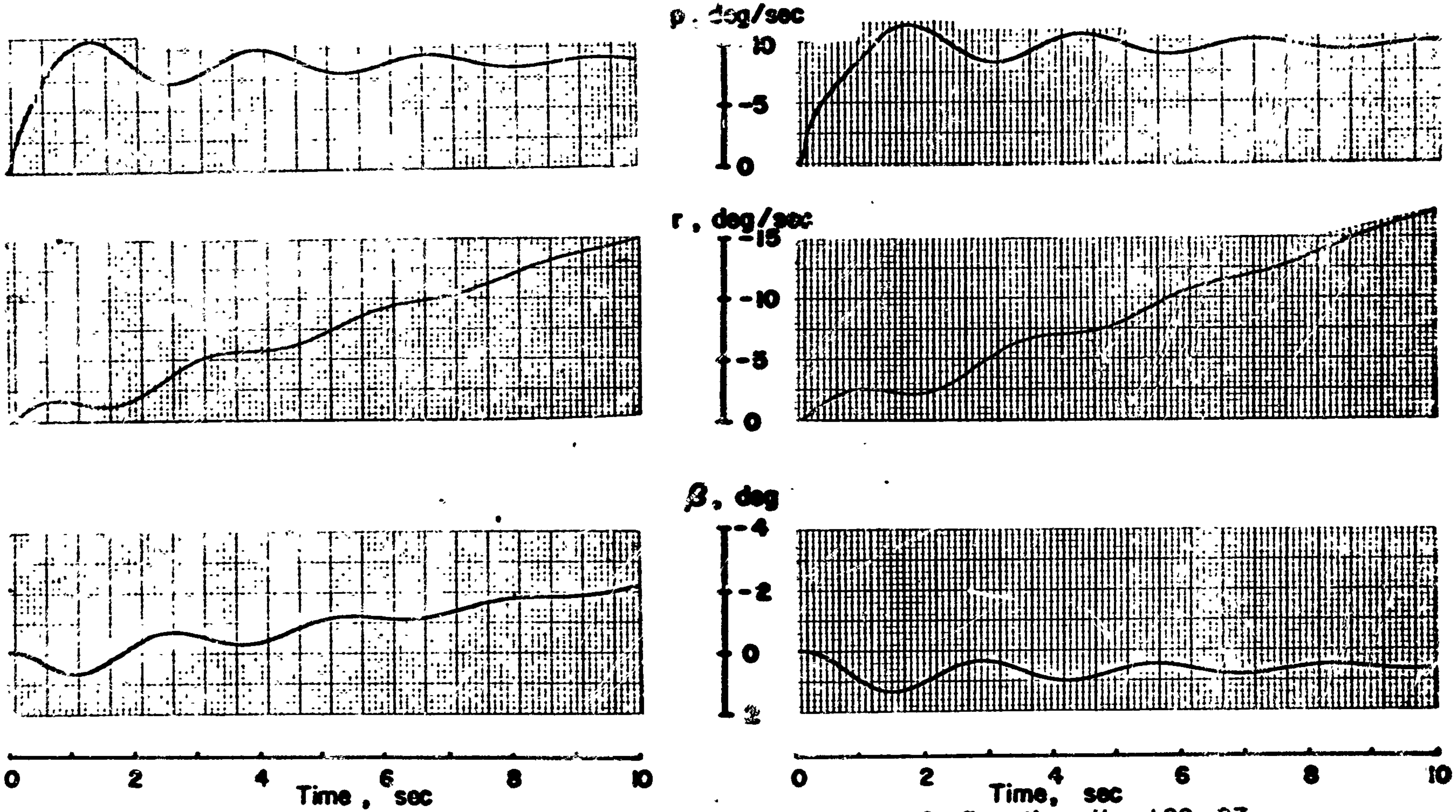
$\omega_\phi = 2.44$, $\zeta_\phi = .05$, $\omega_d = 2.3$, $\zeta_d = .1$

$N_p = .45$, $N_{\delta a}/L_{\delta a} = -.009$, $\tau_{rm} = .25$

Configuration H - 113 - 09

$\omega_\phi = 2.60$, $\zeta_\phi = .09$, $\omega_d = 2.3$, $\zeta_d = .1$

$N_p = .25$, $N_{\delta a}/L_{\delta a} = .078$, $\tau_{rm} = .25$

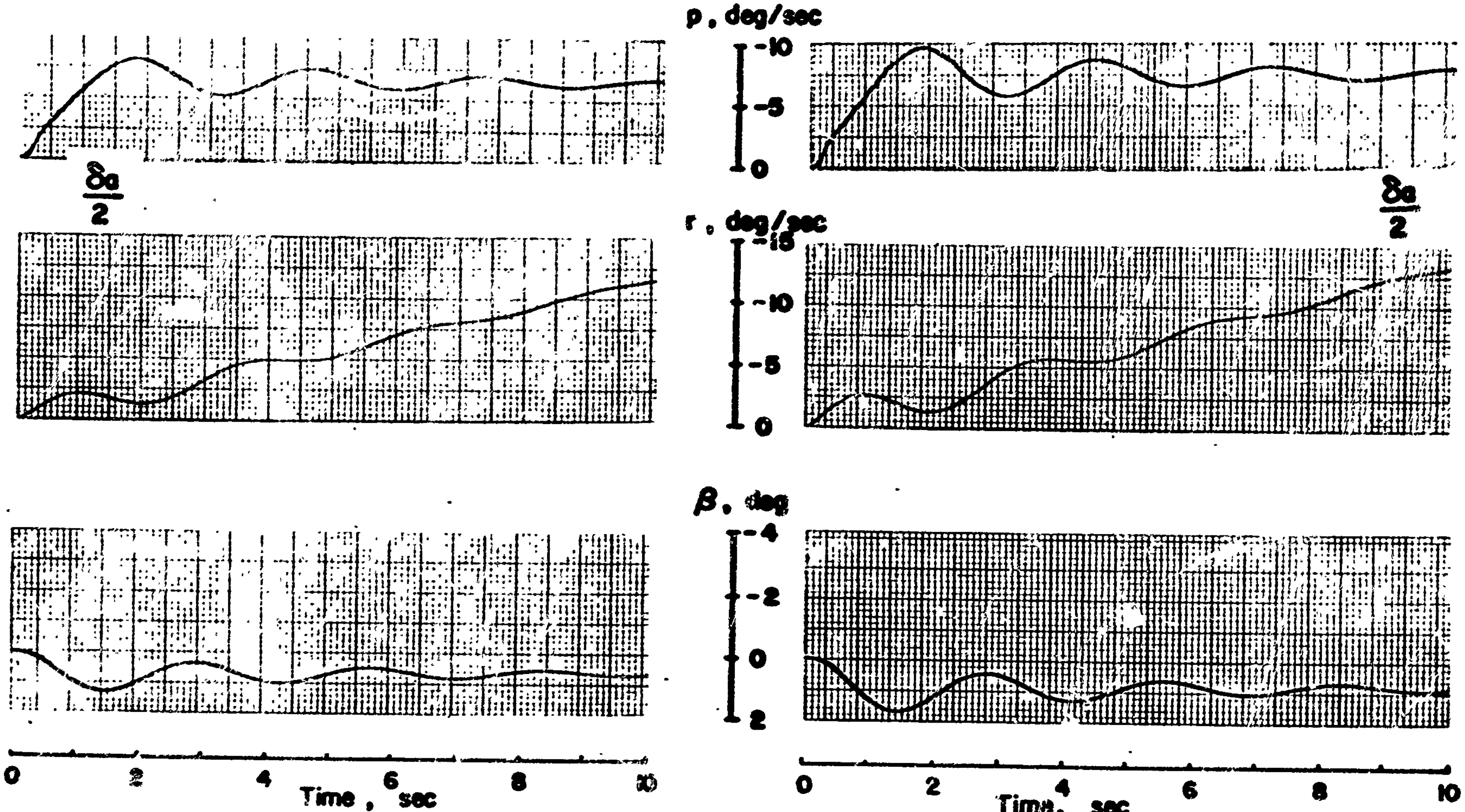


Configuration H - 113 - 26

$\omega_\phi = 2.60$, $\zeta_\phi = .26$, $\omega_d = 2.3$, $\zeta_d = .1$
$N_p = -.35$, $N_{\delta a}/L_{\delta a} = .215$, $\tau_{im} = .25$

Configuration H - 120 - 07

$\omega_\phi = 2.76$, $\zeta_\phi = .07$, $\omega_d = 2.3$, $\zeta_d = .1$
$N_p = .35$, $N_{\delta a}/L_{\delta a} = .112$, $\tau_{m} = .25$



Configuration H - 132 - 06

$\omega_\phi = 3.04$, $\zeta_\phi = .06$, $\omega_d = 2.3$, $\zeta_d = 1$

$N_p = 35$, $N_{\delta a}/L_{\delta a} = .215$, $\tau_{rm} = .25$

Configuration H - 142 - 06

$\omega_\phi = 3.27$, $\zeta_\phi = .06$, $\omega_d = 2.3$, $\zeta_d = .1$

$N_p = .35$, $N_{\delta a}/L_{\delta a} = .302$, $\tau_{rm} = .25$